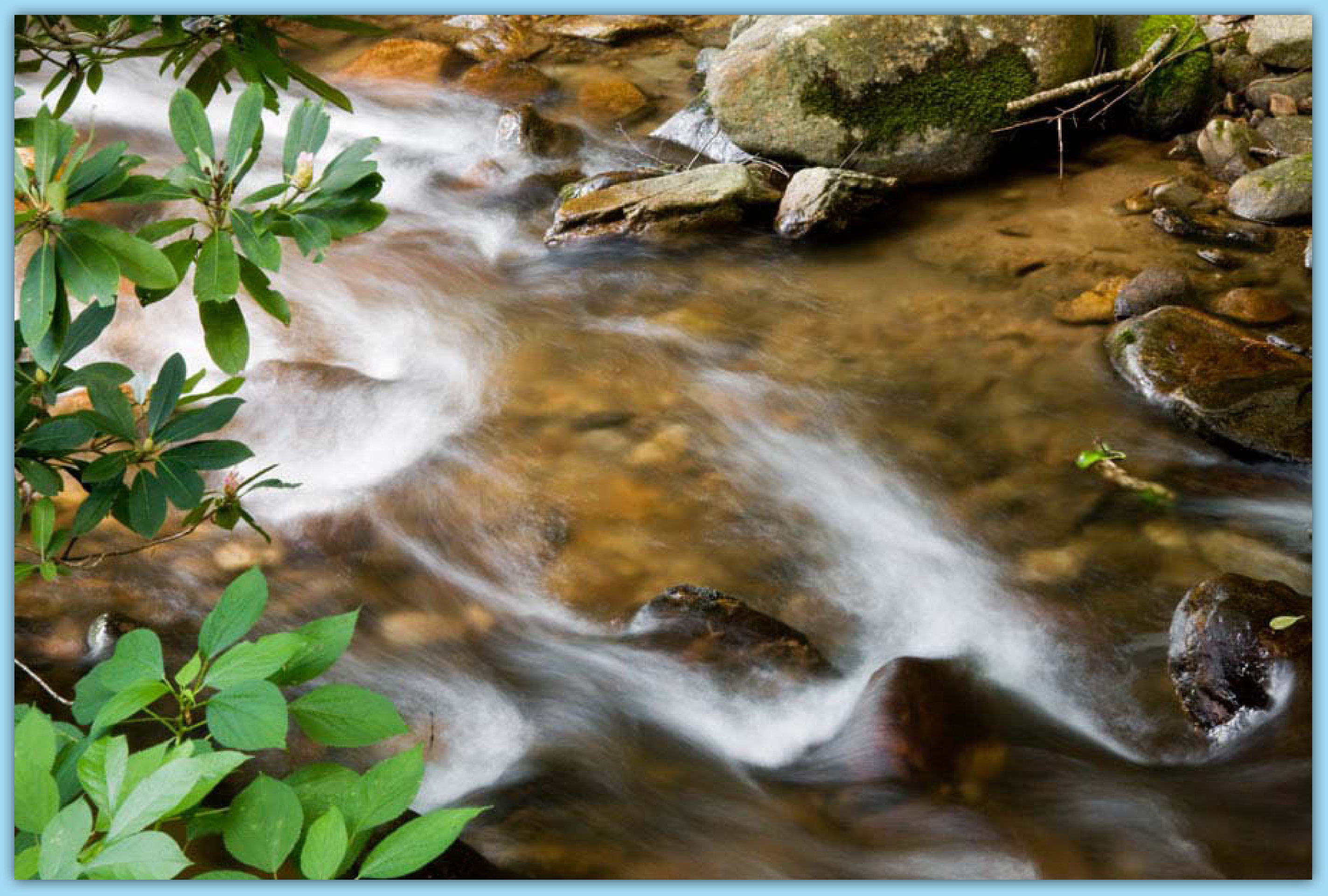
Workshop on Nonstationarity, Hydrologic Frequency Analysis, and Water Management

January 13-15, 2010
Boulder, Colorado

Colorado Water Institute
Information Series No. 109



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- Levi Brekke, Dave Raff, Chuck Hennig (U.S. Bureau of Reclamation)
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- U.S. Bureau of Reclamation
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When referring to this publication, please use the following citation:

Olsen, J. Rolf, Julie Kiang and Reagan Waskom, (editors). 2010. Workshop on Nonstationarity, Hydrologic Frequency Analysis, and Water Management. Colorado Water Institute Information Series No. 109. www.cwi.colostate.edu

This publication was partially funded by the U.S. Army Corps of Engineers. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government and Colorado Satate University.

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Executive Summary

Julie Kiang, U.S. Geological Survey; Rolf Olsen, U.S. Army Corps of Engineers; Reagan Waskom, Colorado Water Institute

An underlying assumption of traditional hydrologic frequency analysis is that climate, and hence the frequency of hydrologic events, is stationary, or unchanging over time. A stationary series is relatively easy to forecast: one simply predicts that statistical properties will be the same in the future as they have been in the past. Anthropogenic climate change and better understanding of decadal and multi-decadal climate variability present a challenge to the validity of this assumption.

The Workshop on Nonstationarity, Hydrologic Frequency Analysis, and Water Management was organized to present and discuss possible operational alternatives to the assumption of stationarity in hydrologic frequency analysis. The workshop was held in Boulder, Colorado from January 13-15, 2010, and brought together researchers and practitioners from the U.S. and international institutions. Understanding the limits of existing methods and exploring possible alternatives for the future is of interest to many federal agencies and other institutions, and this workshop was organized by key federal water agencies (U.S. Army Corps of Engineers (USACE), U.S. Bureau of Reclamation (Reclamation), U.S. Geological Survey (USGS), National Oceanic and Atmospheric Administration (NOAA), Environmental Protection Agency (EPA)) as well as the International Center for Integrated Water Resources Management (ICIWaRM) and Colorado State University.

Water managers have always known our world is inherently nonstationary, and they routinely deal with this in management and planning. Changes in land use, declining groundwater levels, and urbanization are all examples of nonstationarity within a watershed. The Intergovernmental Panel on Climate Change (IPCC) describe another potential source of nonstationarity when stating that "Climate change challenges the traditional assumption that past hydrological experience provides a good guide to future conditions" (Bates et al., 2008). The relevance of this problem depends on the time horizon—operational decisions occur on a very short interval, while water supply planning may have a 50-year or longer time scale. Although several recent academic articles have criticized the assumption of stationarity, it is not apparent what, if any, alternative methods should be used as a replacement.

Uncertainty is a given in water resources planning. The tails of the hydrologic frequency distribution, floods and droughts, are of the most concern for water management. With increasing demands on water resources and larger populations in vulnerable areas, floods and droughts have become more expensive and disruptive. Future climate variability and change may increase our uncertainty about future floods and droughts, thus requiring us to develop a broader understanding of the range of possible hydrologic futures that we may face. System planners must consider both safety and economic optimization. Given nonstationarity, what are the best planning guidelines? This is not a rhetorical question, but one that water managers and planners must find a solution for. What guidance can climate and water scientists give these professionals?

The workshop objectives were (1) to discuss in detail how water management agencies should plan and manage water resources in the face of nonstationarity, and (2) to form a coordinated action plan to help the agencies move forward.

The workshop and this report were organized around three main themes:

1. Understanding nonstationarity through data analysis and statistical methods
2. Forecasting future hydrologic frequency through the use of climate model information
3. Decision making with a highly uncertain future

Also presented during the workshop and in this report are perspectives from water managers who are facing possible climate change, both in the U.S. and internationally. All of this material is book-ended by an introduction to the implications of nonstationarity for water management and concluding thoughts.

This report begins with introductory papers by Robert Hirsch (USGS), Jerry Webb (USACE), and Gene Stakhiv (ICIWaRM), who have each been working in the field of hydrology and water management for decades. Each presents their perspective on how the assumption of stationarity impacts hydrologic frequency analysis and water management, and whether changes need to be made to existing methods. Hirsch asserts that water managers need to move towards new approaches to planning and management that consider nonstationarity through the use of both climate model projections and analysis of long-term hydrologic records. Webb states that no applied hydrologist ever believed there was true stationarity and notes that even though current methods of analysis have flaws and new methods may be needed, it is also critical to use methods that are understood, accepted, and consistent across the nation. Stakhiv adds that both hydrologic and economic factors play an important role in decision-making and both must be considered if the overall decision-making framework is changed.

These existing methods are then summarized by senior engineers from USACE, Beth Faber and J. Rolf Olsen. Nate Snorteland and Pat Foley, also from USACE, then provide examples of how nonstationarity is being considered for dam safety and flood frequency estimation.

The next section of this report focuses on what information can be gleaned from the historical record of climatic and hydrologic variables. If climate is changing, it may be possible to detect changes in flood frequency or drought frequency by examining the historical record. Harry Lins (USGS) and Timothy Cohn (USGS) discuss issues with trend analysis undertaken for this purpose. Demetris Koutsoyiannis (National Technical University of Athens) provides a perspective on how long term persistence needs to be distinguished from anthropogenic climate change. While acknowledging these issues with trend detection, Gabriele Villarini (Princeton University) provides examples of such work for floods in the U.S., and Geoffrey Bonnin (NOAA) presents an analysis of changes in precipitation frequency. In conjunction with data analysis to detect trends, researchers are also investigating possible means of using this information to inform estimates of future flood frequency. Perspectives are offered by Jery Stedinger (Cornell University), Balaji Rajagopalan (Colorado State University), and Taha Ouarda (Institut National de la Recherche Scientifique, Canada), and Richard Vogel (Tufts University).

Some discussion at the workshop focused on Bulletin 17B (U.S. Interagency Advisory Committee on Water Data, 1982), which provides the current uniform flood frequency techniques used by U.S. federal agencies. Many attendees observed that the bulletin has not been updated in nearly 30 years, and that better statistical methods are now available. A working group is developing recommendations for changes to Bulletin 17B, but they currently do not plan to offer suggestions for incorporating nonstationarity into flood frequency estimation.

Current research on using climate model information for water planning is discussed in the next section of this report. Levi Brekke (Reclamation) discusses different approaches for utilizing projections from general circulation models (GCMs). Michael Dettinger (USGS) gives a perspective on how climate model information can be useful, despite the uncertainty which accompanies it. He focuses on an example of how flood causing mechanisms may be changing in California. It may also be possible to use climate model information to estimate future flood frequency, as discussed by David Raff (Reclamation). Throughout the discussion on climate models, the uncertainty in model results was a recurring point. David Stainforth (London School of Economics) suggests that we are not yet ready to constrain that uncertainty. Rather, we need to understand fully model limitations and uncertainty to minimize the risk posed by possible misuse of model results.

Decision-making challenges under nonstationarity are addressed next, and workshop participants noted that climate uncertainty will affect both economic analysis and engineering design. Water managers need to recognize that estimates for the likelihood of future hydrologic events may be very uncertain, and that designs based on these estimates of future probabilities may not be reliable. Methods that acknowledge these uncertainties are discussed by Casey Brown (University of Massachusetts). The traditional approach to incorporating climate change information into decision making has been to develop possible scenarios and to then test the water system using those scenarios. Brown suggests an inverted approach, whereby stakeholders first determine what conditions pose problems to the water system and scientists then try to assess the plausibility of those conditions occurring. Flexible management strategies can then be used to help cope with identified risks. Water managers may also need to adopt alternatives that perform well for many possible future scenarios. As presented by Robert Lempert (RAND), robust planning gives water managers the ability to deal with changes or surprises from any source by focusing on robustness rather than optimality.

Finally, this report provides some examples of how water agencies or other institutions are dealing with the additional uncertainty about the future created by possible changes to climate. Mark Waage (Denver Water) presents options for incorporating nonstationarity into planning that are being considered by Denver Water. Jim Prairie (Reclamation) presents an example of using a blend of information from instrumental records, paleo records, and climate projections to develop planning scenarios. Jeffrey Yang (EPA) presents ideas for analyzing the effects of precipitation frequency changes on water infrastructure. Special attention was given to how nonstationarity is being considered internationally, and include perspectives from Nigel Arnell (University of Reading, United Kingdom), Ken Strzepek (World Bank), Zbigniew Kundzewicz

(Polish Academy of Sciences), and Kuniyoshi Takeuchi (International Center for Water Hazards and Risk Management, Japan).

In summary, a number of conclusions were shared by workshop participants, including the fact that while the water management community has never believed that hydroclimatic processes are stationary, there is a need to move away from stationary risk assessment models in order to design systems for future robustness and resiliency. Federal water agencies need to make a concerted effort to develop methods that adequately incorporate these ideas into practice. Asked to summarize the workshop's findings, Dennis Lettenmaier (University of Washington) states that while low frequency time series variability is an interesting scientific question, it is not a productive area of study if one's goal is to prepare water resource systems for climate change. Instead, he suggests that scientists focus their efforts on using nontraditional data for hydrologic predictions, understanding the nature of ongoing hydrologic change, and rethinking the methods currently used for flood risk estimation. Gerald Galloway (University of Maryland) notes that practitioners have immediate needs and that the scientific and planning communities need to move forward quickly to provide useful information and tools. The workshop's organizing committee provides additional concluding thoughts and next steps as the final paper in this volume.

Proceedings, slides, and proposed next steps resulting from the workshop will be available on the workshop web site at http://www.cwi.colostate.edu/NonstationarityWorkshop.

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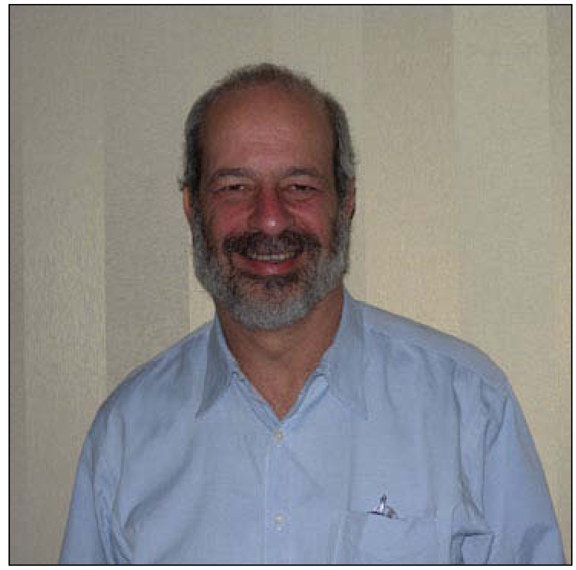
The Problem of Nonstationarity in Water Management: Three Perspectives

A Perspective on Nonstationarity and Water Management

Robert M. Hirsch, U.S. Geological Survey



Abstract

This essay offers some perspectives on issue of nonstationarity due to climate change as a topic of concern to the water management community. Some of the challenges are the following: water management concerns are often focused on the tails of the probability distribution but the ability to predict or detect change is most effective on the central tendency. Hydrologic conditions can be non-stationary due to many types of human actions, but climate change presents special challenges because our ability to predict its impact is still so limited. The inquiry into this issue should follow both an empirical approach and a modeling approach. Precipitation analysis is useful, but it is not a substitute for the analysis of streamflow. The inquiry is difficult because it is so difficult to distinguish between persistence and human-induced trend. There is need for a major emphasis on research on decision-making in the face of this large climate change uncertainty. Finally, the issue of climate change should cause us to place increased emphasis on the continuity of hydrologic records and on the human capital needed to perform continued planning and analysis in the changing world we face.

Introduction

Much discussion and debate has come up since several my colleagues and I published a perspectives article in Science Magazine about two years ago (Milly, *et al*., 2008) regarding stationarity and water management. Our purpose in writing it was to get scientists and engineers to think more about these issues. I think we were clear in saying that we really didn't have answers, but rather that we had questions and wanted to present some challenges to the community to move towards new approaches to analysis, planning, and management. I still believe that we don't have the answers but we are perhaps getting better at posing the questions. In that spirit I'm going to make eight specific points in this talk. They are a combination of observation, paradoxes, and problems. I hope that these ideas will nudge everyone towards some new ways of thinking about water resources.

For water planning and water management, most of the important questions are about the tails of the distribution and not about the center of the distribution. Anything relating to floods, of course, is on the upper tail. Anything that relates to water supply is on the lower tail and things like the mean annual discharge are all rather irrelevant to most water supply, water quality, and hazard management issues. The exception to this generalization is the supply of water in regions that are at the point of consuming all of the renewable supply, which is the state of affairs in many western river basins. The paradox is that the things that are the easiest to predict, as well as to statistically characterize, are related to the center of the distribution, but accurate estimates relating to the tails of the distribution are very hard to come by. Matalas (1990) wrote about the difficulty of testing for changes in variability or skewness as compared to testing for trends in the mean. I think this point is critically important. The characteristics of the probability distribution that we need to know the most about are precisely the things that are hardest to estimate or predict.

A recent review (Barsugli *et al.,* 2009) of the reliability of climate models with respect to water resources predictions suggests a moderate level of confidence about average flows and much less confidence about changes in the extremes. The changing means may be interesting, but what matters most to design or operations are changes in the behavior of the tails. Thus, in the world of predictive models and in the world of statistical analysis, we have the most confidence in statements about the least important aspects of hydrology, and the least confidence in the most important aspects. As a consequence, even after the last few decades during which the scientific community has been exploring climate change in relationship to water resources, we need to be clear with all audiences about just how little we actually know about these important potential changes in water resources.

The second point I want to make is that we, the hydrologic and engineering community, generally include nonstationarity considerations into water planning and management decisions. We consider nonstationarity in those cases where we have a strong scientific basis for including that in our analysis. Examples include: the nonstationarity that arises from urbanization of our watersheds and the changes in flood frequency distributions that occur; or groundwater drawdowns resulting in diminished base flow; or man-made reservoirs that reduce peak flows and increase low flows. We would be derelict in our responsibilities if we did not include these kinds of changes.

Figure 1 is an example of the role that groundwater depletion plays in streamflow, in this case, particularly, minimum in-stream flow. This figure shows the San Pedro River in Arizona, a record from 1936 to 2008. The annual minimum daily discharge has gone from typically 0.06 to 0.14 cubic meters per second as its annual minimum to now hitting zero on a fairly regular basis with most of the recent years having an annual minimum less that 0.05 cubic meters per second. This is not about climate change. It is about the depletion of groundwater in that watershed (Thomas, 2006).

Another example is the Spokane River at Spokane, Washington, an area, again, where there's been a lot of groundwater development (Hsieh, P.A. *et al.,* 2007). Looking at the annual seven-day low flows from 1890 to 2004, the trend in annual 7-day minima is downward from around 50 cubic meters per second to around 20 cubic meters per second.

We would be irresponsible not to include these in planning or operational analyses. They could have a profound influence on our conclusions about future water supply, future habitat, future base-flow water quality, or future assimilative capacity of these rivers. The question is, do we have a basis for including the climate-related ones, and that's going to be a major part of what I'm going to say. My point here is that we should always include nonstationarity to the extent to which we can describe and understand it. I would argue that we may not be as diligent as we should be about considering even these better understood forms of nonstationarity. Keeping our understanding of the behavior of river systems current is an important challenge for the profession.

So, what it boils down to is not a question of whether or not to consider climate change in water planning and management, but rather what do we know well enough to include in our planning and management techniques. One climate-related aspect of nonstationarity that I think is abundantly clear and ready to be applied is the fact that we are seeing warming, and we are seeing a change in the rain and snow dynamics. What we know is that for river basins where snow has been an important component of the hydrology in the past, we are seeing a change to more rain and less snow. In certain cold regions we see more hydrologic variability in the coldest months because in the past they may have always been in a frozen state and any new precipitation fell as snow, whereas now they may experience some melting episodes and some rain events interspersed within the cold and/or snowy periods. The generally warmer conditions are leading to an earlier onset of the spring snowmelt period.

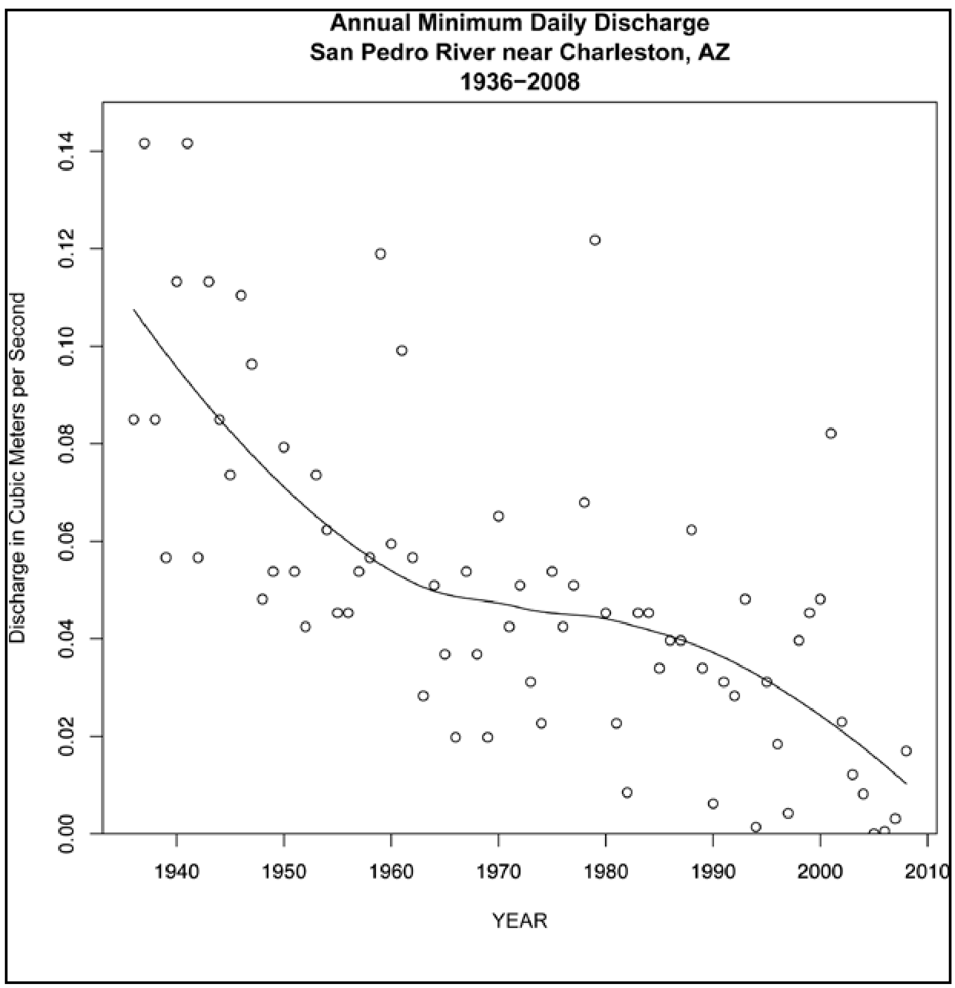


Figure 1. Annual Minimum Daily Discharge, San Pedro River near Charleston, AZ, 1936-2008. Solid line is a local polynomial regression fit.

We are seeing these timing shifts, and those need to be considered in any studies of system operation or design. Harking back to my first point, about changes in means versus changes in extremes, this is an example were we really do know something about changing mean behavior, but there remain some major questions about the extremes in these snowy regions: do we see changes in floods or low-flows? I think the jury is still out as to whether these timing shifts associated with climate warming are actually turning into real flood or low-flow magnitude changes or not. I think it's an important area for research.

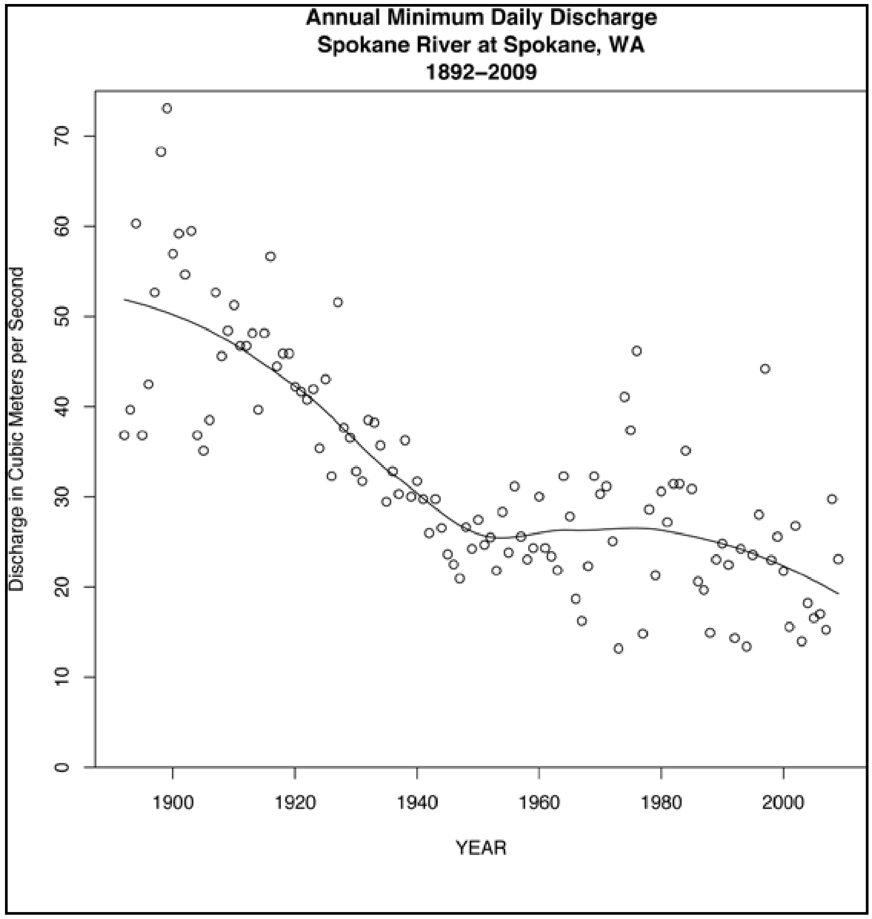


Figure 2. Annual Minimum Daily Discharge, Spokane River at Spokane, WA, 1892-2009. Solid line is a local polynomial regression fit.

The third point is that research related to climate change and water resources really needs to follow two paths simultaneously. And the two paths need to communicate with each other. What are the two paths?

The first one is the use of predictive climate models; and I would argue, this is the dominant path. The approach used here is to take climate model output, and by various approaches, "downscale" the outputs to be appropriate and reasonable input variables to drive hydrologic models which are then used in simulations of system operations.

But the other path we must follow is to view the past century as an unplanned experiment. Mankind has put a lot of greenhouse gases into the atmosphere over the past century. Global CO_2 is about 35 percent higher than it was at the beginning of the industrial revolution. It's very logical to expect that this change in the radiative properties of the atmosphere has already changed the hydrologic cycle. Under this second path, I would argue that we need to use this experiment that's going on today, and tease out everything we can possibly tease out of the hydrologic record and see what we can learn from it. Although we only have one Earth and thus only one run of this experiment, in another sense we have many experimental subjects. These are the individual watersheds. Each one is responding in its own way to the changing global atmosphere. Looking at many watersheds for which we have data from before there were substantial additions of greenhouse gases and from the last several decades when there have been a rapidly-increasing level of greenhouse gases, we may be able to learn how this "experiment" plays out in watersheds of different sizes and different geologic and climatic characteristics.

I would argue that both of these paths are extremely flawed. There are weaknesses and holes that one can poke in both approaches. But they are the only methods that we have at this point, and we need to pursue both of them and look to see to what extent they are pointing us in the same direction, with similar conclusions -- although it's possible they could both be wrong -- or whether they're diverging. We need to have a much higher level of communication between the two different communities and cross-checking between both of them.

As I said, both have severe limitations. I'm not going to spend a lot of time on limitations of the predictive climate models. Some of the weaknesses relate to simulation of precipitation, especially intense precipitation, to simulation of orographic effects, and difficulties in reproducing long-term persistence driven by quasi-periodic ocean phenomena such as El Niño.

The Water Utilities Climate Alliance (Barsugli *et al*., 2009) "options report" presents a thoughtful summary table of the reliability of climate models for water resources applications. Here is my summary of key entries on that table.

Issue	Reliability of climate model output
Shift in seasonality – snow areas	Medium-High
Shift in seasonality – non-snow	Medium-Low
Water supplies – variability in yield	Medium-Low
Seasonal floods	Medium-Low
Major storms/cyclones	Low
Flash floods	Very low

The only place that the word "high" appears here, and that's "medium to high," is on the subject of the shifts in seasonality in snowy areas, and every one of the other characteristics is listed as either medium to low, low, or very low. I know a lot of people in this room are interested in floods, and the three variables that relate to floods are all in these rather low categories. Not a very hopeful sign from a group of climate experts, including those who are strong advocates for the use of modeling.

Is downscaling the answer? And I know there are many in this room who are involved in that process. In my conversations with experts on climate modeling and hydrology I've learned that there are many potential flaws in this approach, associated with some of the inherent inaccuracies of the climate models and also some related to the way that climate model results are captured simply as changes to precipitation and temperature rather than as changes to many aspects of the entire water and energy balance at the land-atmosphere interface. As concerned as I am with the downscaling approach I believe it should still be pursued and improved, but there should also be a vigorous research effort at the same time to see if downscaling can properly hindcast the hydrologic changes (or lack of changes) that have been observed to date.

The empirical approaches have severe flaws to it as well. One of those flaws is the difficulty in sorting out what might be a land-use signal from a climate-related signal, because there are so few hydrologic measurements at locations that are completely free of any land-use related changes. The other is that there may be significant nonlinear effects, so that if we see a change in hydrology associated with the changes that have occurred to date in greenhouse gases, it doesn't mean that that's going to be a change that will continue in a linear manner. There may be major hydrologic changes, particularly if we get important shifts in circulation and storm tracks.

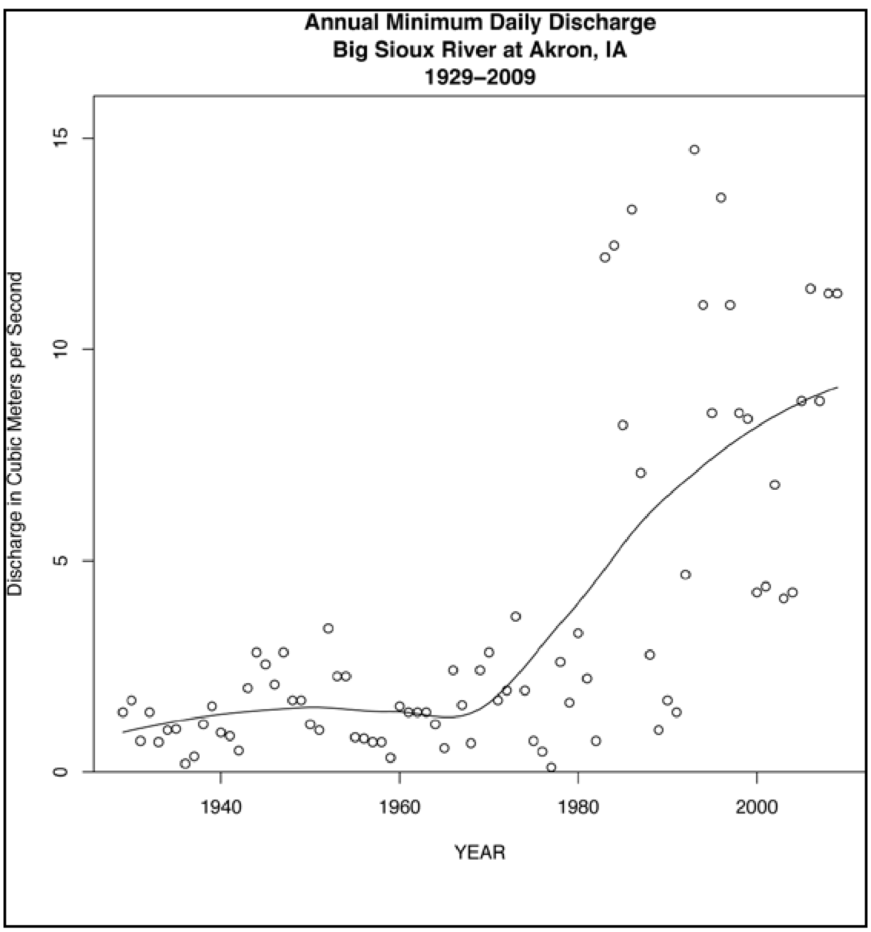


Figure 3. Annual Minimum Daily Discharge, Big Sioux River at Akron, IA, 1929-2009. Solid line is a local polynomial regression fit.

But I think both approaches really have to be carried through. With respect to the second of those, viewing the past century as an unplanned experiment, there needs to be a diverse set of approaches taken to that problem. There is no one proper analytical approach. I would argue that the hydrologic literature is very thin at the present time on the analysis of the treasure trove of both precipitation as well as runoff and groundwater data that we have accumulated.

My fourth point is that analysis of precipitation is useful, but it is not a substitute for the analysis of streamflow or groundwater levels. We need to be careful that we don't assume that observed changes in precipitation variables such as one-day precipitation or number of dry days will translate simply and directly to changes in streamflow. For

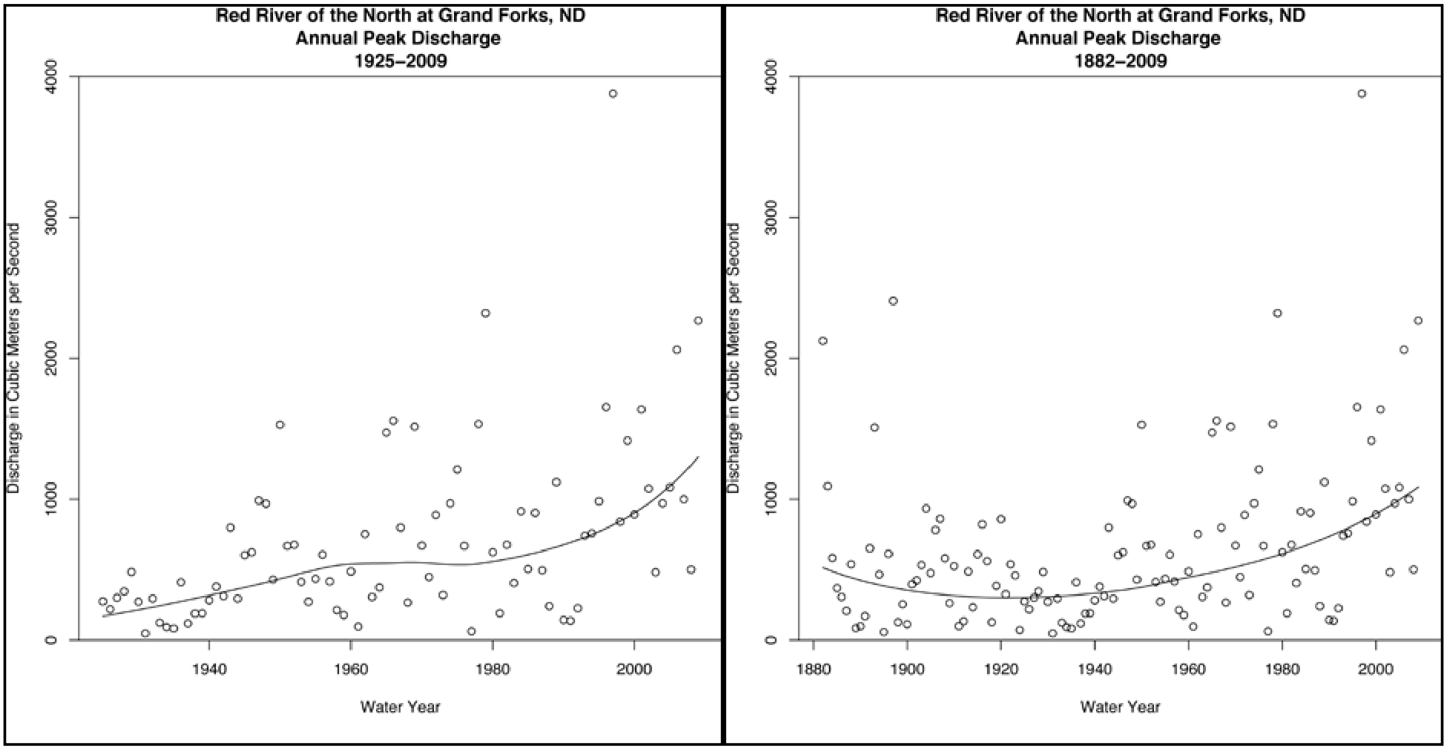


Figure 4. Annual Peak Discharge, Red River of the North at Grand Forks, ND. Solid line is a local polynomial regression fit. Left panel is 1925-2009. Right panel is 1882-2009.

example, some of the greatest floods that we've observed in the United States in the last several decades have really been a part of events that were months in duration. The two great Midwestern floods, of 1993 and 2008, or the Red River floods of 1997 or 2009 have been a result of many months of high precipitation, punctuated with some short-term high precipitation or temperature events. Other reasons why trends in precipitation may not directly translate into changes in streamflow include changes in antecedent soil moisture. The climate modelers tell us that we're going to have drier soils in parts of the U.S. Increased precipitation, or more intense precipitation, falling on drier soils, may or may not lead to larger floods. Another factor is changes in frozen ground conditions. We may have areas that previously had frozen ground at the time of the flood-producing events which may not have frozen ground today. Again, these are things that makes it difficult to just translate precipitation change into a flooding change. Contradictions between precipitation trend studies and streamflow trend studies are not necessarily illogical. Hydrologic responses such as streamflow or groundwater levels can be thought of as a convolution integral of precipitation and the changing climate may bring about changes in the response function. In short, analysis of precipitation trends is important but it is not a substitute for analysis of trends in streamflow or groundwater levels.

Point number five: persistence and human-induced trend are very easily confused. Hurst (1951) taught us about persistence many years ago. We learned that the natural pattern is for wet years to tend to follow wet years and for dry years to tend to follow dry years. Matalas (1990) commented that "…a trend in the short run may be part of an oscillation in the long run." In recent years we've learned some things about quasi-periodic variations like El Niño, Pacific Decadal Oscillation and Atlantic Multi-decadal Oscillation, and even the ice ages. We have learned that these oscillations can have significant impacts on hydrology. We also know that these phenomena are still beyond the limits of our ability to predict. Given what we have learned about these sources of long-term persistence, we need to be very careful to avoid falling into the trap of seeing a pattern that plays out over several decades and calling it a trend. The best protection we can have against this trap is to use very long hydrologic records. This doesn't entirely solve the problem but it can provide some protection. We believe that there are some physical mechanisms behind this behavior, although we are far from understanding the persistence that we actually see in hydrologic records. I'll show you some examples of what I mean and how easily confused we can be.

Figure 3 is an example of the annual minimum daily discharge of the Big Sioux River at Akron, Iowa. It drains out of South Dakota, Minnesota, and Iowa. A change shows up here about 1980. This kind of change is not limited to just one river. Many rivers in this area show a similar pattern of increased low flows around that time. Something significant happened in

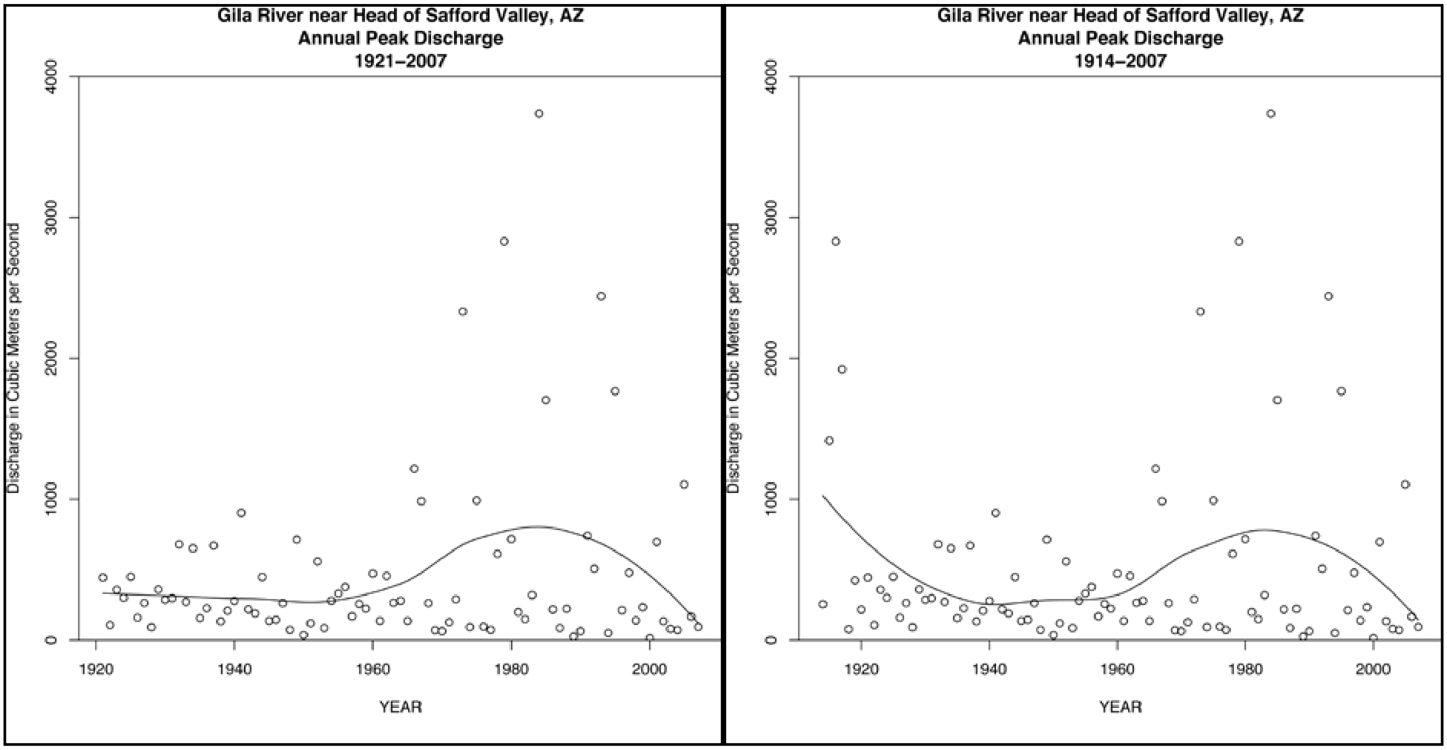


Figure 5. Annual Peak Discharge, Gila River near Head of Safford Valley, AZ. Solid line is a local polynomial regression fit. Left panel is 1921-2007. Right panel is 1914-2007

these basins and we do not understand it. It is much too abrupt to be associated specifically with the long-term greenhouse effect. But it just shows how dramatically hydrologic behaviors can change.

Figure 4 an example from an area of the Nation that has been experiencing extraordinary changes in flood magnitudes in recent decades. It is the Red River of the North at Grand Forks, North Dakota. The left panel shows the annual peak discharges for the years 1925 to 2007. The plot shows a local polynomial regression fit which shows a strong increase from 1925 to about 1960, then a relatively level period to 1980 and then a steep and perhaps accelerating rise since that time. If we run a regression of the log of discharge versus water year we get a trend slope of 20 percent per decade (which is statistically highly significant). Looking at this result it would be easy to conclude that floods are getting larger over time and this would be very consistent with a hypothesis that increased greenhouse gases are driving this increase.

However, the record actually begins in 1882 (the right panel of Figure 4), and if we show the data back to that point we get a very different picture. We see a more complex picture. The fitted curve suggests a period of decrease from 1882 through about 1920 followed up an upwards trend from 1920 to the present. A regression analysis now gives an upwards slope (also highly significant) but of only 8 percent per decade. The addition of 43 years at the beginning of this record results in a major change in the inference one might draw. Now we would say that although there has been some increase in flood magnitudes over time, the pattern is no longer very consistent with a hypothesis that this is driven by greenhouse gas increases in the atmosphere. The high values in the 19th century are inconsistent with this hypothesis. In fact, one could put forward the argument that there are two populations of annual floods at this location. A population that spanned the years of about 1900 to 1941, and another population that existed before 1900 and after 1942. Without the benefit of the longer record we could easily conclude that the data were highly supportive of a greenhouse-gas driven trend in flood magnitudes, but with it we find ourselves having to entertain other highly plausible hypotheses about shifting population that take place at time scales of many decades. The data don't negate the possibility that greenhouse forcing is a significant factor here, but they make it much more difficult to argue for this data set as a clear demonstration of the effect of enhanced greenhouse gas forcing on flood magnitudes.

Figure 5 is yet another example of the same point. This is the Gila River at the head of Safford Valley Arizona. If we only evaluated the record from 1921 to 1960 (left panel of Figure 5) and did flood frequency analysis using that period, our estimate of the 100-year flood would be 1000 cubic meters per second (using the Log Pearson III distribution). Using this estimate, the record from 1960 to present would contain 8 so-called "100-year floods" (the expected number of 100 year floods during this period is only 0.5 floods). Clearly, an estimate of the 100-year flood using data from 1921 to 1960 would be viewed as ridiculous, and such a result would suggest that floods are responding to the greenhouse effect and shifting the flood frequency distribution upwards over time. The right panel of Figure 5 shows the data back to the actual beginning of the record in 1914. If our flood frequency analysis had been done with all the data up to 1960, we would find that the estimated 100-year flood would now be about 2,500 cubic meters per second, and this level would only have been exceeded 2 times in the years 1961-2007. Inferences about greenhouse-gas increases driving increased flooding are not well supported by data set such as this one. This record is much more consistent with a concept of quasi-periodic behavior or multiple population.

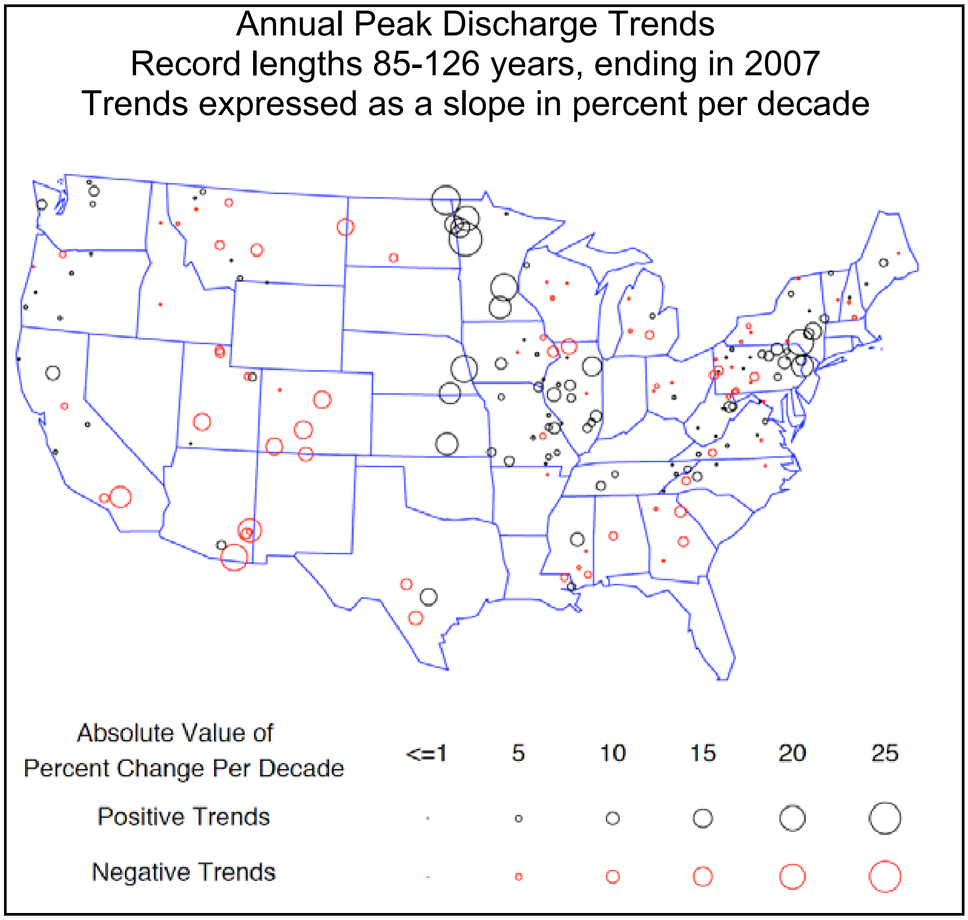


Figure 6. Annual Peak Discharge Trends. Record lengths range from 85-126 years, all ending in Water Year 2007. Trend slopes are expressed as percentage change per decade, based on a linear regression of the log of the annual peak discharge versus Water Year. The black circles indicate upwards trends, and red circles indicate downward trends. Circle diameters are proportional to trend magnitude.

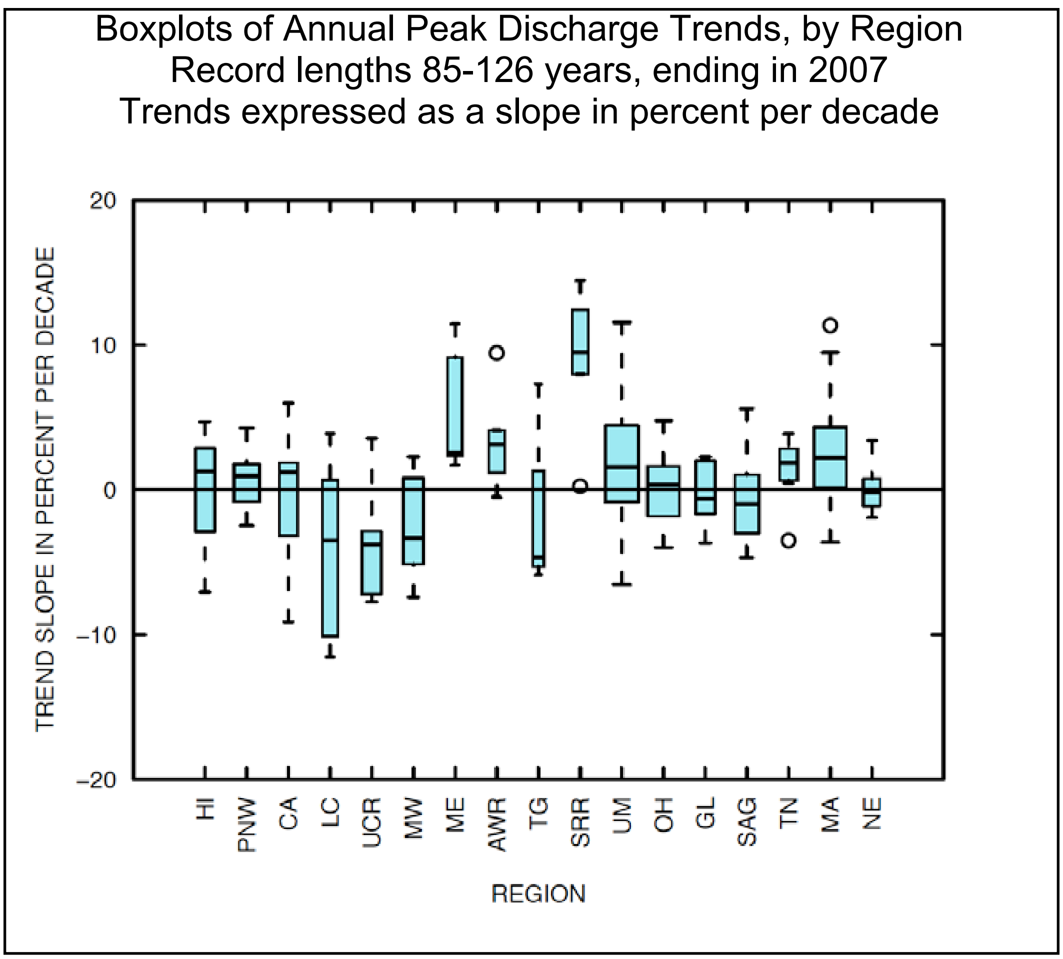
What these examples tell us is that hydrologic records can have a high degree of persistence. It suggests three ideas that need to be considered in the empirical analysis of hydrologic data. One is that persistence can be a real problem, but that problem can be reduced by using longer data sets. Data sets of only a few decades in length can easily point to strong trends that are simply an artifact of some quasi-periodic variation. The second is that explicit consideration of persistent climate phenomena can be helpful in understanding the true underlying trends that may be present. Some of the persistence we see in these examples may be explained on the basis of phenomena such as El Niño. Third, it shows that frequency estimates that are based on short records can be very inaccurate not only for reasons of lack of fit and sampling error, but also because shorter records may not have provided us with a full range of behaviors that we can expect from the system. People have asked me “How should I incorporate long-term climate change into my frequency estimates?” I respond by saying that I don’t think we have a particularly good answer to that question, but we can say this: Your starting place should be an up-to-date frequency analysis. You should also strive to bring in paleo-data and historical information just to broaden your perspective on the kind of variability that can exist at this site. If the hydrology is changing over time, we want to make sure that our estimates incorporate the newest data and the extremes of the distant past. Too often, we use flood frequency estimates that don’t include the most recent data. This would be unwise even if we had no concern about nonstationarity, but becomes dangerous in the presence of either nonstationarity or strong persistence.

What do we actually know about the amount of trend we can actually see in the records we have? Figure 6 based on an analysis of 198 USGS streamgages in the coterminous United States that have operated for more than 85 years and which have no significant upstream regulation or urbanization. The circles represent the magnitude of the trend over their period of record, the black circles represent increasing trends and the red circles represent decreasing trends. The trends are expressed in percentage change per decade. These records range from as short as 85 years to as long as 126 years. Similar analyses were done with subsets of these data that used more consistent starting dates for the records analyzed. The broad pattern of the results at record lengths of 60 and 80 years were very similar to what is shown here.What we see is a pattern in which large parts of the nation show predominantly downward trends (most of the area west of the 100th meridian plus the southeast) but also shows two areas with strongly positive trends (along the eastern edge of the Great Plains and east into Illinois and another area that runs from eastern Pennsylvania through New England). These patterns can also be represented in boxplots of the trend slopes organized by region as in Figure 7.

The regions are arranged essentially along a west to east transect and are generally based on the standard water resources regions of the US (with a few modifications). The labels are defined in the figure caption.

The pattern is interesting. Four of these regions show very strongly propensity toward positive trends (Missouri Basin East; Souris, Rainy, Red; Tennessee, and Middle Atlantic) and four are very strongly negative (Lower Colorado: Upper Colorado, Great Basin, and Rio Grande; the Missouri Basin West; and Texas Gulf). The pattern is very much one of decreasing flood magnitudes in the more arid parts of the nation and increasing floods in the wetter areas, but particularly the cooler wet areas rather than the warm wet areas. I would also add that the area with the most extreme result, the Souris, Rainy, Red region is one where we have some of the longest records and some excellent paleo-hydrology information. The conclusion of many who have studied the hydrology of this region is that the hydrology has gone through a series of rather abrupt shifts in the last few hundred years. In particular, we know that much of the 19th century was a period with a number of very large floods, then 1900 – 1942 was a period in which flood magnitudes were much lower, and then since 1942 the size of floods has generally been increasing. Some have argued that the system might best be characterized as having two statistical populations of floods, with transitions between them taking place at time scales of many decades. This long-term perspective suggests that the behavior is one of persistence and random shifts between populations rather than a system driven by greenhouse forcing. Of course, the correct answer may be that it is some combination of the two.

My sixth point is that we need a new multidisciplinary attack on water resources planning and management, given the high degree of uncertainty about the potential changes in water resources from drivers such as climate change, but also from land use change, and ground-water depletion or other human actions on the landscape. This is a point made in Milly *et al.* (2008), "Stationarity is Dead: Whither Water Management." The point we made there was that the basis of all of our engineering, economics, and decision theory that emerged from the Harvard Water Program (Maass, *et al.*, 1962) implicitly assumed that streamflow is a stationary process, and engineering-economic task was to do some kind of optimization on a risk versus cost trade-off.



The abbreviations are defined as follows:

HI=Hawaii

PNW=Pacific Northwest plus Alaska

CA=California

LC=Lower Colorado

UCR=Upper Colorado and Great Basin and Rio Grande

MW=Western portion of the Missouri River Basin (west of 100o)

ME=Eastern portion of the Missouri River Basin

AWR=Arkansas, White, Red, and Lower Mississippi Basins

TG=Texas Gulf

SRR=Souris, Rainy, Red

UM=Upper Mississippi

OH=Ohio

GL=Great Lakes

SAG=South Atlantic Gulf

TN=Tennessee

MA=Middle Atlantic

NE=New England

Figure 7. Boxplots of Annual Peak Discharge Trends, by Region. Record lengths range from 85-126 years, all ending in Water Year 2007. Trend slopes are expressed as percentage change per decade, based on a linear regression of the log of the annual peak discharge versus Water Year. Box widths are proportional to the square root of the sample size. The Regions are based on the Water Resources Regions of the US, with some modifications.

Once we recognize that we have nonstationarity for a variety of reasons, things like urbanization, groundwater development, as well as the climate issue, we really have to rethink the approach, and it's going to take a concerted effort by a combination of statisticians, economists, operations researchers, hydrologists, climatologists, and civil engineers working together in a think tank kind of environment to create a whole new approach to decision making, given that we know that our climate and other drivers of the hydrologic system are all changing. "Finding a suitable successor is crucial to human adaptation to climate change" (Milly *et al.,* 2008). An excellent discussion of ideas about decision-making under uncertainty, as it relates to the question of climate change can be found in Morgan, *et al.,* 2009.

My seventh point is that we need to redouble our efforts to observe the hydrologic system, describe what we see, and apply what we see. I'm not just talking about observations. I'm also talking about interpretations and the incorporation of this new knowledge into water resources design and operation.

My approach is to say, "It is nonstationarity. Get over it." The important point is to avoid putting the focus on hypothesis tests that just try to figure out whether it is changing or not. Rather, we should put our emphasis on describing and understanding the changes that are occurring in the hydrologic system considering the full range of possible drivers: for example, land use change, dam building and removal, groundwater development, as well as climate drivers.

Another quote from Milly, *et al.,* 2008: "In a non-stationary world, continuity of observations is crucial." To make this point about the importance of measurements I turn to a favorite paper on the subject by Ralph Keeling (2008) who tells the story of Dave Keeling (his father) and the efforts he undertook to develop and then sustain the monitoring of atmospheric CO_2 at the Mauna Loa Observatory, and the scientific interpretation of those data.

I know that some of us hydrologists have what I call "CO_2 envy" (see Vörösmarty, 2002). We wish we had a time series that was as clean and understandable and clear as this to help us tell our story of change. The atmospheric scientists are dealing with a well-mixed fluid and one where the change is large in relationship to natural variability. Hydrologists deal with a poorly mixed fluid (water in the atmosphere and on land) and one for which natural variability is very large in comparison to temporal change. These differences make the task interpretation of our records much more difficult than the task of the atmospheric chemists, but we must strive to collect the data, interpret it, and describe to others the story it contains.

Ralph Keeling wrote this short paper that tells how difficult it was for his father to continue to get funded to collect this absolutely crucial data on the condition of the planet. The people who reviewed his proposal in the funding agencies said "Where's the hypothesis? This is just monitoring." To quote from Ralph Keeling: "A continuing challenge to long-term Earth observations is the prejudice against science that is not directly aimed at hypothesis testing. At a time when the planet is being propelled by human action […], we cannot afford such a rigid view of the scientific enterprise." In other words, among the most important scientific efforts to undertake are those that measure the state of the planet. These will lead to the hypotheses and will be the basis for our learning how the planet operates and provide the reality against which the models can be tested.

Keeling goes on to say that: "The only way we can figure out what is happening to our planet is to measure it. And this means tracking the changes, decade after decade, and poring over the records."

And in the cases of my agency, the USGS, and our colleagues at the National Weather Service, I think of the importance of bringing flood and low-flow frequency analyses (USGS) and precipitation frequency, intensity, and duration analyses (NWS) up to date. We are both making efforts on it, but I would argue both of us are behind the curve in being able to provide the Nation with that kind of up-to-date information that is needed. Regardless of whether we think climate change is important to engineering design and operations we need to base it on the most up-to-date information.

There is another important issue here and that is the continuity of records. Recognizing that the world is non-stationary really heightens the importance of keeping our longest observational records going. The only way we will observe change and potentially sort out trend from persistence is to have records that stretch towards 100 years and beyond. What has been disturbing many of us in the hydrologic community is the difficulty that we have in keeping the funding going so that we can keep the streamgages operating. If we just look at streamgages that have operated for at least 30 years, we had to shut down about 100 of them in 2007 due to funding gaps. These losses of long record stations have had their ups and downs. There were about 150 losses per year in the mid 1990's, only about 20 losses in 2001 (a year of improved streamgaging budgets), but it has been on the rise again in recent years. To provide a more concrete example in one part of the Nation we can look at the Pacific Northwest. At the end of 1979 we had 317 streamgages operating that had started operations in 1930 or before. Today, we have 220 of these still operating, a loss of 31 percent of the total. Given the issues of snowfall, snowpack, streamflow timing, and instream flow for fisheries in this region, this kind of loss of monitoring assets is troubling to say the least.

My eighth and final point is that a very important part of this story of adaptation of water resources to climate change is really about the need for human capital. The next generation of water resources professionals (planners, designers, operators, researchers) need to be educated and they need to be employed in the agencies and companies that do the analyses to keep our water resource systems abreast with the changing hydrologic system. So many of the analyses of important characteristics of our watersheds (e.g. low flows, flood volumes, flood peaks, flood hazard zones) are seriously out of date and need to be updated on a continuous basis to provide the foundation of knowledge on which we can plan and operate our systems. Furthermore, as our climate changes there will be many hydrologic changes that we will need to track and understand (soil moisture, frozen ground, nutrient dynamics, algal dynamics, and many other topics). Effective planning and operations depends on having on staff, or on contract, a workforce that understands hydrology and atmospheric science and which is able to devote the time needed to describe and understand the changes that our water resources are undergoing and to make thoughtful projections of how the system will evolve decades into the future. It may be that preparation for the future depends much more on graduate and undergraduate education and staffing levels of water agencies than it does on the pursuit of highly sophisticated research agendas.

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Biography

Robert M. Hirsch currently serves as a Research Hydrologist at USGS. From 1994 through May 2008, he served as the Chief Hydrologist of the U.S. Geological Survey. In this capacity, Dr. Hirsch was responsible for all U.S. Geological Survey (USGS) water science programs. These programs encompass research and monitoring of the nation's groundwater and surface water resources including issues of water quantity as well as quality. Since 2003 he has served as the co-chair of the Subcommittee on Water Availability and Quality of the Committee on Environment and Natural Resources of the National Science and Technology Council, and in this role he has been instrumental in developing interagency priorities for water science and technology.

Hirsch earned a Ph.D. from the Johns Hopkins University Department of Geography and Environmental Enginnering. He began his USGS career in 1976 as a hydrologist and has conducted research on water supply, water quality, pollutant transport, and flood frequency analysis. He had a leading role in the development of several major USGS programs: 1) the National Water Quality Assessment (NAWQA) Program: 2) the National Streamflow Information Program (NSIP); and 3) the National Water Information System Web (NWISWeb). He has received numerous honors from the Federal Government and from non-governmental organizations, including the 2006 American Water Resources Association's William C. Ackermann Medal for Excellence in Water Management, and has twice been conferred the rank of Meritorious Senior Executive by the President of the United States. He is a recipient of the USGS "Eugene M. Shoemaker Award for Lifetime Achievement in Communications." He is co-author of the textbook "Statistical Methods in Water Resources." Dr. Hirsch is a Fellow of the American Association for the Advancement of Science and an active member of the American Geophysical Union and the American Water Resources Association. He has testified before congressional committees on many occasions and presented keynote addresses at many water-related meetings across the nation.

Since returning to a research position he has focused his efforts on methods for better documenting and understanding long-term changes in water quantity and quality in rivers. He is exploring century-scale trends in flooding nationwide and nutrient transport trends over several decades in rivers tributary to the Chesapeake Bay and the Gulf of Mexico. Clear communication of the results and their implications for policy is an integral part of this research.

Nonstationarity in Water Management: USACE Perspective

Jerry W. Webb and Kathleen D. White, U.S. Army Corps of Engineers

Abstract

During the early- to mid-20th century era of Federal infrastructure building, engineers were forced to design water resources projects using what would now be considered relatively simple tools on the basis of short observed hydrology records. Lacking sophisticated dynamic process models and computational techniques, two primary factors enabled them to design and construct the many projects still in operation today: 1) inherent conservatism in design and 2) the assumption of stationary hydrology (i.e., that hydrology varies within an unchanging envelope of natural variability, so that the past accurately represents the future). Conservatism in design (e.g., factors of safety) has been replaced in many cases by risk-based design. While alleviating issues associated with the economic cost of conservatism, risk-based design is highly dependent on projections of future conditions and the inherent uncertainty of the system. The assumption of stationary hydrology allowed water resources managers to transform complex and uncertain hydrology into a form tractable for planning, engineering, and management of water resources projects given the resources available at the time. Today, there is growing recognition that, despite its successful application in the past, the assumption of stationarity may no longer be valid. However, before this assumption can be overturned, Federal agencies require an alternate approach that provides consistent, repeatable analytical results supporting resilient infrastructure design. This paper presents the US Army Corps of Engineers perspective on the issue of nonstationarity.

Water resources infrastructure planning and design relies on an understanding of past conditions and projection of future conditions impacting rainfall and runoff. In many cases, engineers assumed that time series data representing rainfall or runoff were stationary, that is, the mean, variance, and autocorrelation of the series do not vary over time (e.g., Vandaele 1983). Essentially, stationarity assumes that hydrology varies within an unchanging envelope of natural variability, so that the past accurately represents the future (Milly et al 2008). The assumption of stationarity in hydrologic data has been a basic assumption used by practicing engineers for many years in the planning, design, and operation of water resources projects such as dams, levees, floodwalls, canals, bridges, and culverts. Hydrologic engineers have always been aware that this assumption was flawed in the sense that it potentially over-simplifies a complex process (Chow 1964). However, it was a necessary assumption for the planning and design of water resources projects where observed records were relatively short and detailed analytical or dynamic representations of physical processes were not available.

Hydrologic engineers acknowledge that there is uncertainty in any statistical representation of the data. They are particularly concerned with uncertainties associated with extrapolation of historic data beyond limits of the observed data as is commonly done in flood frequency analyses supporting water resources infrastructure design and operating rules. Water resources engineers must apply a significant amount of judgment to the results obtained using analytical and statistical tools as they adapt and normalize historic data to reflect changes in land use, urbanization, and other parameters that can influence runoff. We contend that engineers never accepted the premise that "true" stationarity existed, but simply adopted the assumption of stationarity as a reasonable method to allow historic data to represent estimates of future conditions we could expect as design loading conditions over the life of a water resources project.

Traditional approaches to hydraulic design often combined some stochastic or probabilistic analysis plus a factor of safety to ensure a conservative design that provided resilience to unexpected events. The requirement in the latter part of the 20th century to perform reliability analyses of our infrastructure led to risk-based engineering design and assessment because of the recognition that traditional approaches are inadequate (Cheng et al 1993). This has increased our reliance on accurate projections of future operating conditions with improved understanding of the uncertainties in these projections. At the same time, advances in modeling and computing allowed more detailed exploration of uncertainties and variability, which in turn led to evaluations of the stationarity of time series data.

US Army Corps of Engineers and Stationarity

The US Army Corps of Engineers (USACE) is responsible for the planning, design, operation and maintenance of a variety of water resources projects. The assumption of stationarity has been utilized for decades and appears to have served hydrologic engineers effectively with respect to project performance. Observed climate variability impacts to water resources project operation and trends associated with climate change have highlighted in recent years the need to re-evaluate the assumption of stationarity (Milly et al 2008). The use of a nonstationary model for time series is particularly useful in forecasting future behavior when the mean value estimated from the past may not be relevant in the future (Box et al 1998) as is the case where hydroclimatic variability is experienced (e.g., Hirschboeck 1988). With respect to the historic use of the stationarity assumption in the USACE, we are not aware of any project design deficiencies that been specifically associated with erroneous assumption of stationarity.

If the assumption of stationarity is no longer valid, our society must develop a replacement strategy that will meet planning and design requirements. It is understandable that scientists, statistical experts, and engineers have reason to question continued use of the stationarity assumption. The real problem is the lack of consensus and recommendations for a replacement methodology that can be used by design engineers. It is imperative that these communities of practice – climatologists, statistical experts, and water resources engineers – work together in an effort to develop, test and implement a new approach to addressing the issue of stationarity.

USACE is committed to participating in the development of alternate methodologies that would allow adaptive management of our infrastructure and incorporate climate variability to make our projects more sustainable. That commitment does not constitute authority to incorporate a new strategy in operations of existing projects without going through the appropriate study authorization process.

Stationarity Assumptions in Water Management

From the USACE water management perspective, reservoir operating plans are developed during the initial planning studies to provide flexibility to adapt to whatever flow conditions are expected to prevail on a daily basis (USACE 1982, USACE 1987). There are provisions to temporarily modify the operations during periods of unusual conditions through a deviation approval process. USACE is not authorized to deviate from the authorized water control plans other than through approved deviations and/or permanent changes in operating plans. These operating plans may be included in the Congressional authorizing language and thus may require an act of Congress to change.

We can certainly implement new methodologies in plan formulation of new projects but day-to-day operations of existing projects are much harder to change. Simply changing our assumptions of stationarity is not sufficient to alter existing operations. It is necessary to perform new allocation studies to determine whether new operation plans should be developed and adopted as a result of the studies. Potential changes resulting from movement to nonstationary analyses might initially affect new planning studies and/or re-allocation studies, with the possible exception of those projects that have the authority or flexibility to adaptively manage operations to optimize certain parameters (usually environmental parameters).

Stationarity versus Climate Variability

There is no doubt that changes in global climate have occurred over recent years, and the rate of change in the future is certainly a matter of concern. With respect to assumptions of stationarity, the engineering community of practice should be concerned about changing the methodologies of assessment to better incorporate the uncertainty introduced by the lack of stationarity and to develop acceptable methods to project future conditions. This would mean a modification of Bulletin 17B (IACWD 1982) and other guidance that is currently used in flood frequency analyses and other components of engineering design. The major question for engineers should be: Is there a better means of analysis that we should be using for sustainable and resilient planning, design and operation of our nation's water resources projects?

In the case of sea level rise (SLR), USACE recently updated the policy on how SLR should be considered for sustainability of coastal projects (USACE 2009). This change in policy may result in a change in engineering design criteria for coastal projects. USACE was successful in implementation of a new sea level policy because consensus was achieved among scientists and engineers that global warming and long-term changes in climate would most certainly result in some increase in expected future sea levels, even though the magnitude of the expected rise varies significantly depending on which emissions scenarios, global circulation models, and initial and boundary conditions are utilized.

New Method Development

In order to develop a new methodology that is more representative of expected future loading conditions than the assumption of stationarity, we must achieve some level of consensus on exactly what parameters will be impacted and what range of variation can be expected on a regional basis. The method of implementation must be consistent and reproducible. It appears that much study is needed and a much higher level of collaboration and communication among all the interested stakeholders must be achieved before agreement can be reached.

Until consensus on a new methodology is reached, engineers will continue to use existing procedures even though we recognize that the uncertainty associated with these procedures is increased due to potential impacts of climate variability that may not be captured in the stationarity assumption. When USACE designs a water resources project, we must utilize accepted, consistent design standards in such a manner that would allow others to apply the same data and reproduce the design. USACE accepts that climate variability exists and that uncertainty in design parameters is one result of that variability. Current studies indicate that there is a significant variation in how some design parameters have responded to climate variability when viewed on a regional basis. Studies also indicate that there is a lack of consistency in the trends of design parameter responses on a regional basis. Until these inconsistencies can be resolved and consensus reached on trends that can be expected, the assumption of stationarity will continue to be utilized.

USACE accepts the concept that assumptions of stationarity are flawed and have always been flawed to some extent. We also accept that there are changes occurring in our global climate, and we need to be able to adaptively manage our resources in this changing environment. In order to do this we must maintain data collection programs collecting essential data and we must participate with the scientific community in addressing the stationarity issue. Assumptions of stationarity are just one of many engineering judgment requirements utilized in the application toolbox used by hydrologic engineers. If there is a better assumption or methodology that improves our ability to interpret and apply historic data to estimate future hydrologic conditions, we are receptive to exploring those possibilities. However, it should be noted that changing current methodologies across the hydrologic engineering community of practice will be no trivial task.

USACE is not authorized to modify existing water management operations without going through appropriate studies. These studies must rely on accepted, consistent, reproducible methodologies. In order to meet these requirements climate scientists, statistical experts and water resources engineers must achieve some level of consensus on an improved approach. As long as there is disagreement between scientists and statisticians on an acceptable approach to analysis of climate variability, engineers will be forced to use best engineering practices for plan formulation, design and operation of water resources projects which may include continued use of the assumption of stationarity. The challenge lies in resolving the ambiguity of the various global models and the implementation and adaptation of the models to develop engineering design methodology.

The ultimate solution will require a multi-disciplinary approach and significant effort over several years to develop a complete understanding of our global climate. Once we understand the science we must develop a methodology to apply appropriate statistical uncertainties in the application of these principles to water resources planning activities.

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Biography

Jerry W. Webb has been employed by the U.S. Army Corps of Engineers since May 1974. Since January 2003, he has served as the principal hydrologic and hydraulic engineer for the U.S. Army Corps of Engineers (USACE). He represents USACE in international and national forums as the Corps highest authority in areas of hydrologic engineering. He also serves as the leader of the Hydrologic, Hydraulic, and Coastal Community of Practice within the Headquarters, Engineering and Construction Division. He collaborates with the Chief, Engineering and Construction Division in planning, developing and directing the execution of all aspects of watershed technical policy related to worldwide design and construction mission assigned to USACE. He serves as the principal advisor to the Chief of Engineers and the Directors of Civil Works and Military Programs on engineering and scientific issues related to watershed engineering technologies which impact worldwide design and construction mission. He provides national leadership for the USACE in regard to watershed technologies and represents the Chief of Engineers on complex technical issues with senior level officials in other government agencies, and states policy or influences policy at national conferences or international forums. Mr. Webb has principal responsibility for developing goals, training measures and evaluating the competencies of field activities related to watershed engineering requirements necessary to successfully perform the USACE worldwide design and construction mission. He is a national expert consultant to senior USACE officials and for other federal clients on major, one-of-a-kind projects and programs of local, national or international scope to ensure technical adequacy and to provide, if required, innovative technical solutions.

He has held positions in Memphis District, and Huntington District, as a Civil and Hydraulic engineer. In addition to his federal career, Mr. Webb retired in July 2008 as a Lieutenant Colonel in the West Virginia Air National Guard. He served as the Senior Advisor to the Ministry of Water Resources (MoWR) in Iraq September 2003 through February 2004. Mr. Webb volunteered to serve in the Iraq Reconstruction effort as the Senior Advisor where he was responsible for an organization of 12000+ personnel that operates the oldest water resources systems in the world. The Ministry operates a complex system of 25 major dams and barrages and 275 major irrigation pump stations, produces 17% of the nations electricity, 27,000 kilometers of irrigation channels and 3.25 million hectares of irrigated land. Mr. Webb utilized the experience that he had gained through his 30+ years of service with the Corps of Engineers to meet the challenges of leading and managing the MoWR in the reconstruction effort. Mr. Webb also served as the interim Senior Advisor to the Ministry of Environment for the period January-February 2004.

Practical Approaches to Water Management under Climate Change Uncertainty

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Abstract

Water resources management is in a difficult transition phase, trying to accommodate the large uncertainties associated with climate change, while struggling with implementing a difficult set of principles and institutional changes associated with integrated water resources management (IWRM) and adaptive management (AM). Water management is the principal medium through which many of the projected impacts of global warming will be felt and ameliorated. Many standard hydrological practices, based on assumptions of a stationary climate and variability, can be extended to accommodate numerous aspects of climate uncertainty. Adaptations of various strategies developed by the water management profession to cope with contemporary uncertainties and climate variability can also be effectively employed during this transition period, as a new family of hydrological tools and better climate change models are developed. "Robust decisionmaking" is among the new approaches being advocated for planning and designing water resources infrastructure under climate uncertainty.

Introduction

In order to address the issue of climate change uncertainty in the context of water resources decision-making within the broader framework of IWRM, one must ask what is the nature of those decisions. Even within the bounds of historical climate variability there are difficult decisions that routinely surround basic management actions associated with the design of new infrastructure, reservoir operations, drought management or flood fighting. The complexity of these decisions will inevitably be compounded by global warming, because a great deal more uncertainty associated with unknown states of future climate is introduced into the decision-making process. Decision-makers, politicians and the public at large, all of whom are expected to participate in modern water management decision-making at some level, have a difficult enough time with standard concepts of a 100-year floodplain or a category-5 hurricane storm surge. The expanded uncertainties and unknowns associated with global warming, make such decisions and public participation even more daunting.

In any given region or location planners and designers have to determine a broad set of related issues that are always dependent on the frequencies of hydrologic and precipitation phenomena:

- How high should a levee be, and what is the risk to those living behind it?
- How to characterize and identify a 100-year floodplain?
- How to manage a reservoir to accommodate uncertain spring runoff?
- How much storage in a reservoir should be allocated to irrigation versus other competing future needs?
- How safe is the structure under extreme flood conditions?
- How to size the spillway for a rare flood?
- What criteria should be used to "recertify" flood mitigation structures where the flow frequencies have changed or are in the process of changing?
- How should our procedures on life-cycle infrastructure management and performance accommodate our evolving understanding of climate change?
- What flood/drought frequency distribution should be used in a particular analysis to accommodate climate uncertainty?

Water resources management is essentially bounded by how the extremes – floods and droughts – are defined and characterized, along with methods and standards for reducing the risks to society. Virtually all major infrastructure requires some estimate of what the extreme events have been historically, as the probabilistic basis for structural reliability – i.e. to ensure the hydraulic safety of a structure; as well as for determining the planning and design of a reliable stream or delivery of services associated with the infrastructure. A good knowledge of hydrologic extremes is also needed for setting flood insurance rates, crop insurance, defining floodplain zones and designing storm sewers and highway culverts, etc. In most cases, the extremes and changes we are experiencing are still within the "norms" of natural historical climate variability. Our existing water resources infrastructure was designed to accommodate such order-of-magnitude of variability. In fact, standard engineering practices account for the uncertainties by designing redundancy to account for the uncertainties. Hence, 'levee freeboard' was added onto a 'standard project flood' to accommodate the uncertainties associated with historical climate variability involved in designing levee systems.

This was the equivalent of applying an early version of the 'precautionary principle' to deal with the unknowns – i.e. those aspects of hydrologic phenomena that went beyond conventional risk and uncertainty analysis. Climate uncertainties are not really uncertainties – they are true unknowns, and hence incapable of being estimated based on the current state of climate modelling, making the estimation of these extremes virtually a meaningless exercise for the purposes of water management needs. So, if we are to deal with climate change, a substantially different water management approach needs to be devised – yet based on a foundation of existing principles and evaluation techniques. This approach, essentially an adaptation of existing proven principles and techniques, shall be termed 'robust decision-making' – a process designed to accommodate uncertain scenarios with evaluation and project justification principles that focus less on optimal outcomes and more on 'satisficing' (i.e., producing robust solutions).

The design of new water infrastructure projects presents the biggest challenge in the current circumstances, i.e. the transition period, as the life of a typical project is usually 50 years or more, and encompasses the period when climate change impacts are expected to become more severe. Standard hydrologic methods are still useful, though carefully selected climate scenarios can be applied to test the robustness of the performance of various alternative designs to determine the 'best' (most risk-cost effective) design. However, economic decision criteria and evaluation practices would need to be revised in conjunction with the changes in hydrologic analyses. For example, the choice of the discount rate in any economic analysis, whether it be internal rate of return or classical benefit-cost analysis is the single most important determinant of the economic viability of a water project.

Chracteristics of Water Management

According to the IPCC (2007), climate change is a significant threat to all nations and, in particular, developing nations that are dependent on agriculture for subsistence. Every nation is vulnerable to rare and extreme flood and drought events; the United States is no exception, as was demonstrated by the devastation of hurricane Katrina. The reality is that water management systems are not designed to protect against the full range of possible expected extreme events under what is understood to be contemporary climate variability. They are designed to minimize the combination of risks and costs of a wide range hazards to society. This risk-cost balance is constantly being adjusted by societies – that is why we have relatively safety standards for flood and drought infrastructure reliability set at about a 100-year return period – they approximate that historically determined risk-cost optimum for our systems. Of course, as population density in urban areas increases, these standards may have to change, and begin to approach the risk-averse standards of the Netherlands and Japan. The setting of new design standards and planning criteria are probably the most important aspects of any adaptation strategy. Since the destructive Mississippi River floods of 1993, there has been a movement to increase the flood protection standards of major urban areas in the floodplains to about a 500-year level of flood protection (Interagency Floodplain Management Review Committee, 1994).

For the past 50 years, the US has followed a path of what could be termed 'autonomous adaptation' to climate variability and change, which has proved to be reasonably effective with respect to water resources management (Lettenmaier, et.al, 1999; Lins and Stakhiv, 1998; Olsen, et.al, 1999). There have been very few failures of the nation's water management infrastructure – i.e. where the infrastructure failed before its design capacity was exceeded. It should be remembered that most of the nation's large water infrastructure (locks, dams, levees, irrigation canals and conveyance tunnels) was built in the period between the 1930's through the 1970's – well before the era of sophisticated modeling, risk and reliability analysis and an adequate data base for determining risk and uncertainty associated with climate variability. Yet the structures stand and have performed effectively through a wide range of unanticipated climate variability – in other words they are remarkably robust and resilient.

Though the science of hydrology, hydraulic engineering, watershed modeling and data collection has improved dramatically since the 1970's, especially with the advent of satellite-based data, the dominant changes that influence the design of contemporary hydraulic structures since 1970, have come from the multiobjective planning paradigm, rather than changes in engineering design standards and criteria. The basic standards used for designing hydraulic infrastructure – notions like the 'probable maximum flood'(PMF) for spillway design; or application of a 100-year return period as the basis for traditional levee design and the flood insurance program are based on hundreds of years of engineering experience and empirical analysis. Planning and evaluation principles have changed dramatically during the past 50 years, influenced largely by the ideas of the Harvard water program (Maass, et.al, 1962), and implemented through the planning guidance of the U.S. Water Resources Council (WRC; 1973, 1983). The principal purpose of planning, though, was not to design reliable, robust and resilient hydraulic structures, but to design projects and programs that served a more diverse range of social needs, and adequately accounted for the direct and indirect economic, social and environmental costs, and which optimized net economic benefits, subject to environmental constraints.

The pressure from academia to revise the basic planning and evaluation guidelines of the federal agencies to design more economically efficient projects that encompassed a wider range of purposes, services and outputs, actually reduced the operational reliability, robustness and resiliency of projects, by eliminating a range of engineering 'safety factors' that typically accounted for the hydrologic uncertainties and unknowns and ignorance associated with a highly variable climate, poor models, and inadequate data bases. Ironically, the focus on risk and uncertainty analysis, together with multiobjective optimization effectively reduced much of the engineered redundancy of many projects that were based on the original standards-based paradigm, which explicitly acknowledged the ignorance of hydrologic and hydraulic engineers with respect to climate variability.

These 'safety factors' actually constituted an early and unacknowledged version of the 'no regrets' principle, as well as the 'precautionary principle.' Early engineers knew that there was persistence in the hydrologic record; that there were trends and multi-decadal fluctuations, and understood that there were events that were much larger and more extensive than the short hydrologic records they typically dealt with. They planned for the unknowns by designing system redundancy and adding safety factors. That's why so many projects have functioned under a much wider range of conditions and purposes than designed for, and have repeatedly been adapted to a broader range of needs and conditions by sequential reallocation of storage and changes of operating rules – i.e. have more resilience and robustness than anticipated (Fiering, 1982; Rogers and Fiering, 1986). Furthermore, the addition of numerous other social, cultural, ecological requirements and constraints, along with a host of new project purposes that were never authorized by legislation (recreation, ecological flows, floodplain benefits, etc.) actually reduced the degrees of freedom that operators had to manage such projects in emergencies, and further decreased the robustness and resiliency of each water management infrastructure system. Ironically, but not surprisingly, sustainable development principles have reduced the flexibility of water managers to operate and prepare for uncertainties, contingencies and emergencies, and has created what Hashimoto, et.al have termed 'brittle solutions'.

Conventional Water Resources Decision-Making

What constitutes water sector decision-making? Although hydro-climatologic information about frequencies, magnitude, duration and incidence of precipitation and runoff events are the basic inputs into most water management decisions, they are but precursors to more fundamental economic, environmental and socio-economic information and objectives that typically dominate most water management decisions. In fact, it is the non-hydrologic information that directs and constrains the basic decision rules that societies use to choose from among a wide range of options that can be employed for any given water management problem. Land-use regulations, economic priorities, trade policies, benefit-cost criteria and even the choice of a discount rate in deciding the future value of a stream of benefits and costs derived from a project, are more prominent as decision factors than most hydrologic information.

Despite the best attempts to extract the most information possible from the current suite of General Circulation Models (GCMs) for peering into the future, the best that can be said is that all the models are fairly uniform in the unidirectional increase in temperatures, but offer very little reliability for forecasting precipitation or runoff. What is much more uncertain, verging on the edge of unknowns, is how this translates into precipitation, evaporation, frequency and intensity of droughts, floods, tornados or hurricanes. The information currently available from GCMs is simply inadequate for most operational and design aspects of water sector decisions, and is not expected to be useful for at least another decade. So, we have to resort to extending existing approaches to substitute for the lack of usable information from the GCMs.

Society, and the engineering profession, through a historical accumulation of experience, laws, engineering practices and regulations, has defined a narrower acceptable range of 'expected' events to which it chooses to adapt – hence we have the 100-year floodplain for flood insurance purposes; we design our urban drainage systems for smaller but more frequent events; and we ensure dam safety by designing spillways for very low-probability floods, roughly of a 10,000 year return period. These are societal judgments made on the basis of many factors, including affordability, relative population vulnerability, and national and regional economic benefits. They are not deterministic criteria made on the basis of empirical or simulation modeling. Neither GCM models nor IPCC reports can provide such a determination. Defining social risk tolerance and service reliability is part of a 'social contract' to be determined through the political process coupled with public participation – a continuing 'dialogue' within each society – whether it be for new drugs, nuclear power plants or water infrastructure.

The water resources management sector has developed strategies to deal with periods of high demand and low water availability. There are essentially five ways that water managers have of adapting to climate variability and change:

- Planning new investments, or for capacity expansion (reservoirs, irrigation systems, levees, water supply, wastewater treatment)
- Operation, monitoring and regulation of existing systems to accommodate new uses or conditions (e.g. ecology, climate change, population growth)
- Maintenance and major rehabilitation of existing systems (e.g. dams, barrages, irrigation systems, canals, pumps, etc.)
- Modifications in processes and demands (water conservation, pricing, regulation, legislation) for existing systems and water users
- Introducing new efficient technologies (desalting, biotechnology, drip irrigation, wastewater reuse, recycling, solar energy)

Water resources management, which has evolved with its core principles of adaptive management – i.e. adapting to the risk and uncertainty of considerable climate variability, has employed a variety of tools, in different combinations, to reduce vulnerability, enhance system resiliency and robustness and provide reliable delivery of water-related services. These tools consist of many technological innovations, engineering design changes, multi-objective watershed planning, public participation, regulatory, financial and policy incentives (Kabat, et.al, 2003). However, well-functioning institutions are needed to effectively administer this broad array of fairly complex, dispersed and expensive combinations of management measures. Hence, tackling the central issue of 'governance' is a key aspect of any strategy that intends to deal with climate change adaptation. IWRM is the management framework for achieving sustainable development. Governance and IWRM are the principal means for resolving competition among multi-sectoral demands on a fixed water resources base. Each sector (environment, water supply, sanitation, agriculture, hydropower, navigation/transportation) fashions its own set of management principles, rules and incentives that are maximized, often in conflict with one another.

Integrated Water Resources Management (IWRM)

IWRM is the long-term institutional basis upon which climate change adaptation can be sustained through the coordination of numerous adaptive management strategies in water-related sectors. The ideal IWRM framework advocates a few essential components or prerequisites:

- National water policy which lays out roles, responsibilities and management objectives
- National/regional/river basin water management plans that are consistent with national water policies
- River basin commissions that implement and manage resources according to plans that are updated periodically
- Enabling regulatory and institutional regime, with enforcement mechanisms
- Coordinated federal/state/local management

The essential purpose of IWRM is to manage water more efficiently (use less water, more value per drop, conserve) and effectively (delivery of reliable services, improved performance in each sector). IWRM requires the harmonization of policies, institutions, regulatory frameworks (permits, licenses, monitoring), planning, operations, maintenance and design standards of numerous agencies and departments responsible for one or more aspects of water and related natural resources management. Water management can work effectively (but not efficiently) in fragmented institutional systems (such as the federally-based systems of the U.S., Brazil and Australia as examples), where there is a high degree of decision making transparency, public participation, and adequate financial support for planning and implementation. It does not work well in most other cases where these prerequisites do not exist. Setting up the proper institutional framework is the first step towards IWRM.

Adaptive Management

Adaptive management (and its cousin the 'precautionary principle') are key concepts that are central to the management of the vast network of existing water infrastructure. The keystone of adaptive management is a much improved meteorological and hydrologic data network. Flood and drought contingency preparedness and recovery operations are the leading edge of any adaptive management strategy that is inherently geared to dealing with uncertainty of climate variability and change, and dependent on better forecasting and real-time data collection and analysis. Improvements in seasonal and intra-annual forecasts would offer the greatest positive changes to a broad array of water management functions – especially for agricultural irrigation, which uses approximately 80% of the freshwater resources of the globe, and is essential to most economies of the developing world.

Adaptive management is a decision process that "promotes flexible decision-making that can be adjusted in the face of uncertainties as outcomes from management actions and other events become better understood" (National Research Council, 2004). Adaptation to climate change is a merely a cousin of adaptive management – a continuous process of adjustment and flexible adaptation that attempts to deal with the increasingly rapid changes in our societies, economies and technological changes. Adaptive management is perfectly suited to much of the immediate efforts needed for operational adjustments in the current infrastructure; changes in processes and demands, and maintenance and rehabilitation of existing infrastructure – particularly for irrigation systems and flood risk management in the floodplains of river basins. These are the two water management sectors that would provide the largest and most immediate payoffs in climate change adaptation, by reducing the vulnerabilities of existing systems, improving productivity and water use efficiency, and reducing flood damage losses. Adaptive management may be the most effective way of dealing with future climate impacts under the current evaluation procedures and high degree of uncertainty (Stakhiv and Pietrowsky, 2009).

Vulnerability Assessment

It is useful to differentiate hydrologic runoff sensitivity to climate change from water management vulnerability and societal susceptibility to economic disruptions and dislocation as a consequence of climate change. Hashimoto, et al. (1982) introduced a taxonomy to account for risk and uncertainty inherent in water resources system performance evaluation. It is clear that the five terms listed below simply represent a set of descriptors that characterize and extend the key components of more traditional engineering reliability analysis, i.e., they focus on the sensitivity of parameters and decision variables to considerations of uncertainty, including some aspects of strategic uncertainty. These terms are:

Reliability - a measure of how often a system is likely to fail

Robustness - the economic performance of a system under a range of uncertain conditions

Resiliency - how quickly a system recovers from failure (floods, droughts)

Vulnerability - how severe the consequences of failure may be

Brittleness - the inability of optimal solutions to accommodate unforeseen circumstances related to an uncertain future.

The relative vulnerability of a water resources system, then, is a function of hydrologic sensitivity (as input to the managed system) and the relative performance (robustness) of a water management system as it affects the delivery of services required by society. This is more of a technically defined management function, which can be quantified according to various scenarios of climate change. Societal susceptibility to climate change, on the other hand, depends on numerous factors outside the control of water managers, such as land use regulations, proper allocation of water supplies and population growth and economic policies related to water uses. Without an integrated water management capability, society becomes increasingly susceptible both to population-driven increases in water demands, as well as climate change variability. In other words, susceptibility and vulnerability increases not so much because of increased hydrologic variability, but more as a function of an inadequate institutional infrastructure required to manage those resources. IWRM, coupled with adaptive management, are the two most effective mechanisms to deal with the uncertainties associated with social susceptibility. In many cases, upgrading the institutional capacity of developing nations to implement sound water management practices is the most effective way of reducing vulnerability due to climate change.

- Assess existing statutes, policies and regs for dealing with extremes and contingencies – who has the authority and responsibility for what?
- Who is responsible for climate adaptation planning?
- Who operates and maintains existing water infrastructure? Is it at capacity? Can it serve projected needs? What is needed over next 10-20 years?
- Assess socioeconomic scenarios of growth and development – what does the future look like? How will future demands for resources be met? What is role of water?
- Assess vulnerability to current climate variability – floods and droughts. How will this change under future climate scenarios, and growth in 2050?

Adapting a New Paradigm for Decisionmaking

To more effectively accommodate the new version of the 'precautionary principle', together with the broader aims of 'sustainable development', there will have to be a 'paradigm shift' from the deterministic view embodied in the 'Principles and Guidelines' (WRC; 1973,1983), based on a view of a relatively stationary climate, to a much more flexible set of multi-objective evaluation principles and procedures that more appropriately account for the full range of social, environmental and regional economic dimensions of water infrastructure under a wide range of uncertain climate scenarios. It may require an end to the era of rational analytic optimization to one where robustness and resiliency features are built into water projects – especially more flexible operational elements of a project. But the fundamental changes must come in the economic evaluation principles that are used for project justification (e.g., changing decision rules from "maximize net benefits" to "minimize risk-cost"). The current economic criteria are based on stringent benefit-cost tests or maximizing the internal rate of return. New economic evaluation and decision rules for infrastructure designed to cope with climate uncertainty – i.e. be more robust and resilient – needs to adapt different decision rules, such as maximizing risk-cost effectiveness or minimizing risk-cost. The process has already begun in many federal agencies in order to accommodate the uncertainties associated with planning and designing infrastructure under climate change uncertainty.

There are many improvements in existing conventional approaches that can be made, which fall under the general rubric of 'robust decision making' (RDM). RDM is a framework for making decisions with a large number of highly imperfect forecasts of the future. RDM relies on many plausible futures (e.g. climate change models, historic information, tree ring data, etc.), and then allows analysts and decision makers to identify a series of near-term and long-term actions (options) that are robust across a very wide range of futures. Rather than rely exclusively on a single future or a probabilistic forecast of a possible future, the approach asks what can be done today to set the stage and shape a more desirable future (Lempert, et.al, 2010). The strategy has three complementary components:

- Seeking robust rather than optimal projects or strategies (this requires a substantial revision of current economic and optimization decision rules routinely used in water resources management).
- Employ adaptive strategies to achieve robustness (near-term strategies are explicitly designed with the expectation that they will be revised as better information becomes available)
- Use computer-aided analysis for interactive exploration of hypotheses, options and possibilities.

This sort of strategy has been advocated for the past few decades by water resources practitioners and academicians (e.g., Rogers and Fiering (1986) noted, in an evaluation of how systems analysis and optimization models were being employed by the U. S. federal water management agencies, that there were practical and political limitations on the use of such advanced techniques, and that there were many solutions that were near the global optimum). When coupled with the large uncertainties involved in much of the input data, the use of such models for practical public decisionmaking was problematic, indeed. They concluded by urging that the "…use of optimizing models be softened in favor of systematic analysis. This is consistent with the earlier concept of satisficing proposed by Simon (1957), which looks for solutions that maximize the probability of achieving acceptable (satisfactory) outcomes" rather than searching for optimal, economically efficient solutions. This advice is even more relevant when confronted with climate change uncertainties and unknowns. A practical version of RDM has been developed by water resources planners in the Corps of Engineers and applied successfully under the label of “Shared Vision Planning” (Werick and Palmer, 2008). It has been used most directly for climate change adaptation in two Great Lakes regulation studies for Lake Ontario-St. Lawrence system (LOSL Board, 2006) and the Upper Great Lakes (IUGLS Board, 2009).

Practical Recommendations

Because climate change, like drought, is a ‘creeping’, slowly evolving uncertain phenomenon, it will not serve to catalyze actions in a politicized world that has profound difficulties in dealing with uncertainties that potentially require huge investments upfront to avoid unknown risks. To deal with the unique circumstances of this type of phenomenon, the U. S. Army Corps of Engineers (Secretary of the Army Congressional Testimony; 2007) adopted a pragmatic ‘proactive adaptive management’ approach, comparable to the ‘no regrets’ philosophy espoused by many advocates of climate change adaptation, consisting of the following elements:

- Risk-based planning and design of infrastructure to account for climate uncertainties
- Development of new generation of risk-based design standards for infrastructure responding to extreme events (floods and droughts)
- Life-cycle management of aging infrastructure
- Vulnerability assessment of water infrastructure
- Increased inspections, oversight and regulation of infrastructure during operation and maintenance
- Increased research and development oriented towards climate change and variability
- Develop improved forecasting methods for improved reservoir and emergency operations
- Strengthen interagency collaboration for developing joint procedures and applied research for adapting to climate change
- Strengthen emergency management and preparedness plans for all Corps projects and assist local communities in upgrading their plans and participation.

Operational changes inherently are oriented towards improving the use and performance of the existing water resources delivery systems for all of its designed and de facto uses. For example, most reservoirs, wherever they may be located, undergo periodic reviews of their operating rules, either as part of new and expanded hydrologic records; or new uses or purposes are added (e.g,. recreation, environmental flows, protection of endangered species, etc.). These are the opportunities for updating the drought and flood contingency plans based on new information that could improve the overall resiliency, robustness and reliability of the system. These revisions may take into account changes in peak flood periods, snowmelt timing or updating of flood and drought frequency analysis based on new methods and extended data, along with scenarios based on GCMs that would test the robustness of the operating system. Figure 2 shows the Corps of Engineers various operating procedures and manuals that are related to reservoir management that are routinely revised and adapted as new information becomes available.

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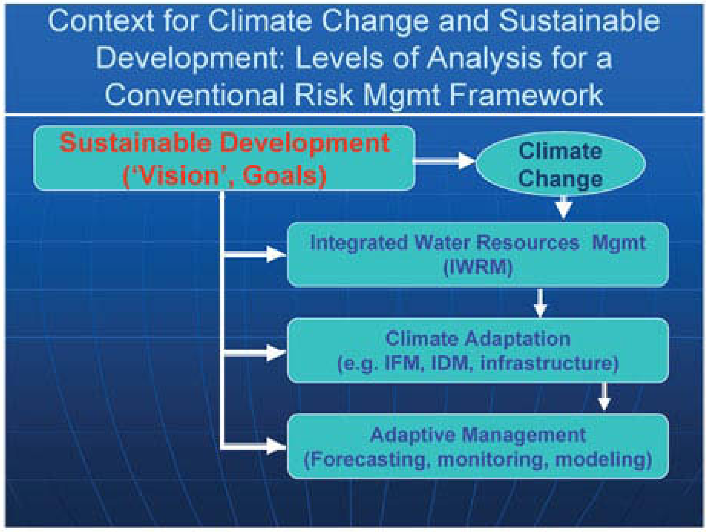
Biography

Eugene Z. Stakhiv is currently appointed as US Co-Director, International Joint Commission (IJC) Upper Great Lakes Study, a five year (2006-2012, $15M study) that will look for more sustainable ways of operating the Great Lakes under various climate scenarios. He is also Technical Director of the recently approved UNESCO International Center for Integrated Water Resources Management (ICIWaRM). Dr. Stakhiv also recently completed a 5-year study, as Co-Director of the Lake Ontario-St. Lawrence Study for the International Joint Commission (2000-2006, $20M study with Canada). He has been at the Corps of Engineers Institute for Water Resources (IWR) for 30 years, and is Senior International Water Advisor. He has also served as Scientific Attache to US UNESCO Ambassador in Paris (May – Aug, 2004). Dr. Stakhiv also served as Senior Advisor to Iraq's Ministry of Irrigation from April 13-Sep 20, 2003. Before that, he was Chief, Planning, Policy and Special Studies Division, Institute for Water Resources (1990-2004). The division helps in formulating practical policies and procedures that the Corps needs to respond to legislation, Administration initiatives and scientific advances. Most of the Corps' national studies of the past decade, such as the National Wetlands Mitigation Study, National Drought Management Study, Federal Infrastructure Strategy and Corps' Shore Protection Study, and currently the National Shoreline Management Study have been conducted by his Division. He served as first Co-chair for IPCC-I Water Resources and Hydrology Committee, and as Lead Author for IPCC-II and IPCC-III. Dr. Stakhiv has extensive international experience, primarily with the World Bank, serving as senior advisor to the water Ministries of Bangladesh, Ukraine, Armenia, Iraq and the Aral Sea Basin countries. Eugene Stakhiv has spent his entire professional career of 40 years with the Corps, and has served as study manager for several large comprehensive river basin studies and metropolitan water supply studies, including Washington, DC and New York City. He has a doctorate in water resources systems engineering from Johns Hopkins University, and has authored nearly 70 published papers and 150 technical reports.



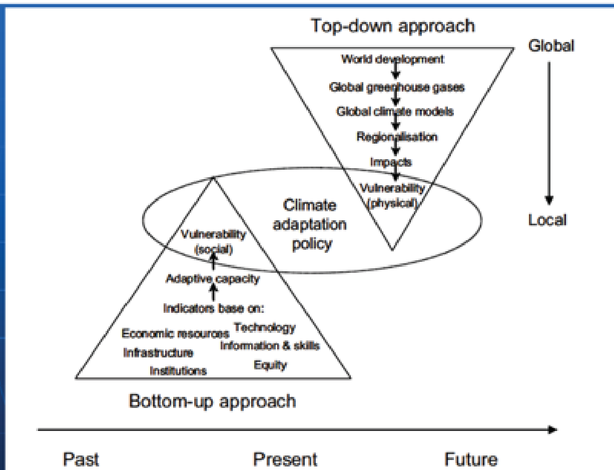
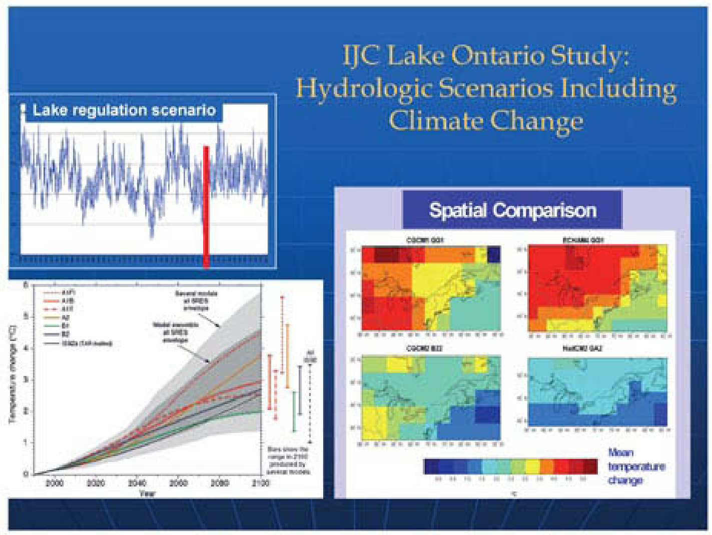
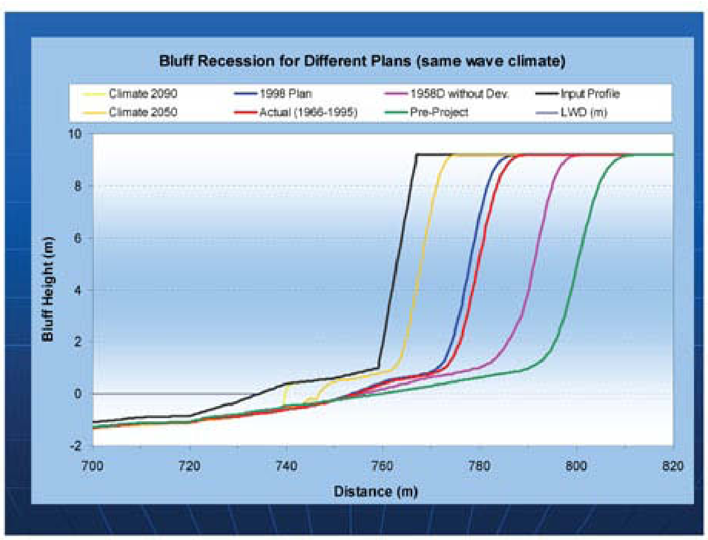


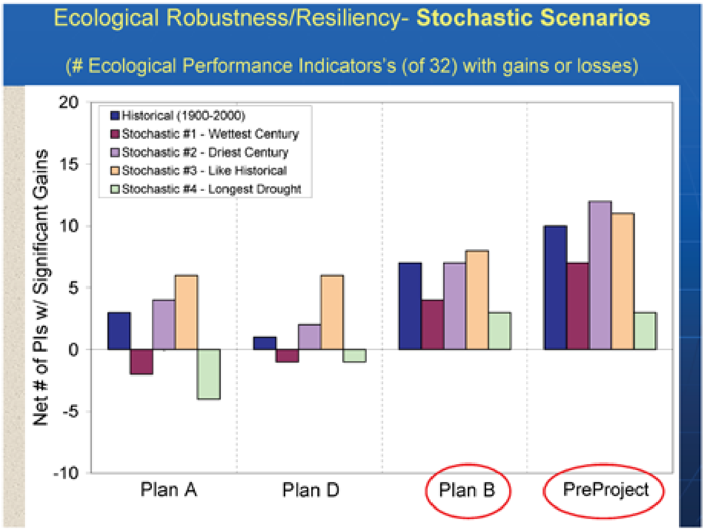
Figure 3.1. "Top-down" and "bottom-up" approaches used to inform adaptation to climate change (from Dessai and Hulme 2004).

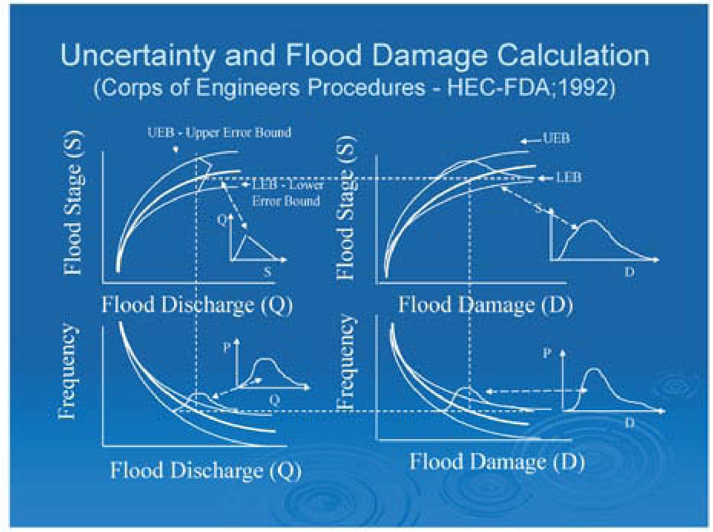




GCM Scenarios: Economic Robustness of Plans IJC Lake Ontario-St. Lawrence Regulation w.r.t Climate Change Scenarios

Avg. ann. net benefits ($US million)	Plan 1958DD	Plan A	Plan B	Plan D	Plan E
		Econ Efficiency	*Environ Quality*	*Combo Benefits*	*Natural Flows*
Plan 1958DD (current plan)	0	7.52	6.48	6.52	-12.30
C1- Hot/Dry	-115.65	34.89	-1.42	20.09	-4.91
C2 - Warm/Dry	-49.52	9.85	4.89	5.25	-34.03
C3 - Hot/Wet	-81.69	21.53	2.61	17.77	-2.46
C4 - Warm/Wet	13.98	8.33	11.78	9.65	-21.38





R&U Flood Damages Analysis

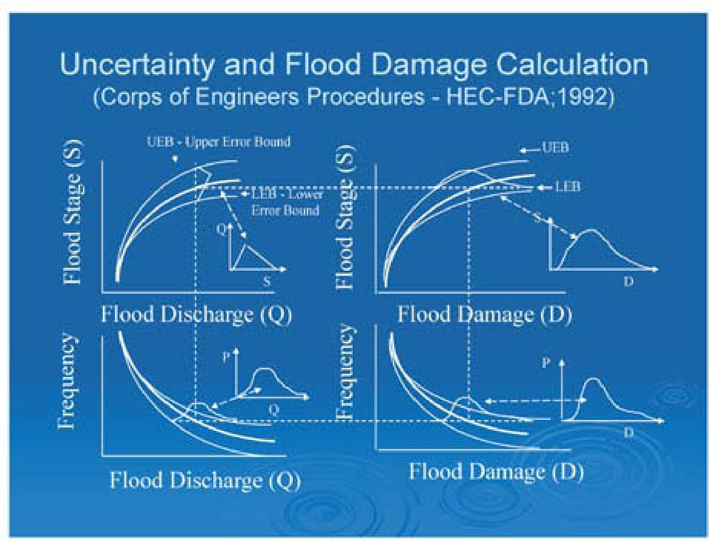
Plan	Expected Annual Damage ($'000)			Probability EAD Reduced Exceeds Indicated Amount ($'000)				
	Without Plan	With Plan	Damage Reduced	0.95	0.75	0.50	0.25	0.05
20 foot levee	575.0	220.0	355.0	290.0	325.0	350.0	380.0	450.0
25 foot levee	575.0	75.0	500.0	370.0	435.0	490.0	550.0	690.0
30 foot levee	575.0	0.0	575.0	410.0	495.0	560.0	630.0	815.0
Channel	575.0	200.0	375.0	300.0	325.0	360.0	400.0	600.0
Detention Basin	575.0	250.0	325.0	200.0	260.0	300.0	330.0	450.0
Relocation	575.0	300.0	275.0	150.0	200.0	260.0	300.0	450.0

Discounted Avg Annual Net Benefits (Benefits – Costs)

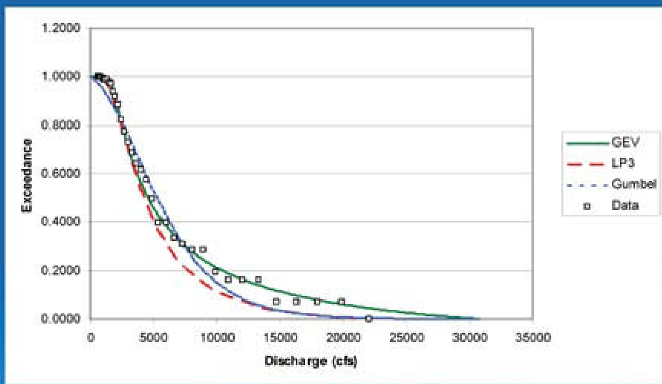
Plan	Expected Annual NED Benefit and NED Cost ($'000)			Probability Net Benefit Exceeds Indicated Amount ($'000)				
	Benefits	Cost	Net Benefits	0.95	0.75	0.50	0.25	0.05
20 foot levee	355.0	300.0	55.0	(25.0)	20.0	53.0	88.0	148.0
25 foot levee	500.0	400.0	100.0	(40.0)	35.0	91.0	152.0	280.0
30 foot levee	575.0	550.0	25.0	155.0	(60.0)	12.0	88.0	261.0
Channel	375.0	300.0	75.0	(30.0)	15.0	70.0	120.0	205.0
Detention Basin	325.0	275.0	50.0	(20.0)	18.0	50.0	75.0	150.0
Relocation	275.0	475.0	(200.0)	300.0	(250.0)	(210.0)	(170.0)	(50.0)

Long-term Risk of Failure

Plan	Annual Performance (Expected Annual Probability of Design Being Exceeded)	Equivalent Long-term Risk (Probability of Exceedance Over the Indicated Time Period)		
		10 Years	20 Years	50 Years
W/O Project	0.250	0.944	0.997	1.000
20 foot Levee	0.020	0.183	0.332	0.636
25 foot Levee	0.010	0.096	0.182	0.395
30 foot Levee	0.001	0.010	0.020	0.049
Channel	0.025	0.224	0.397	0.718
Detention Basin	0.030	0.263	0.456	0.782
Relocation	0.100	0.651	0.878	0.995

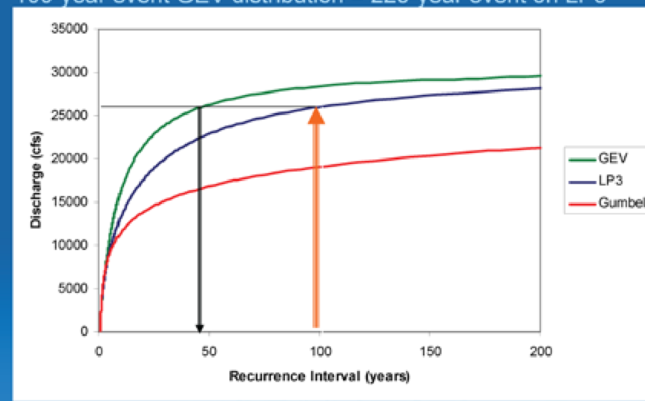


Hydrologic Excedance graph



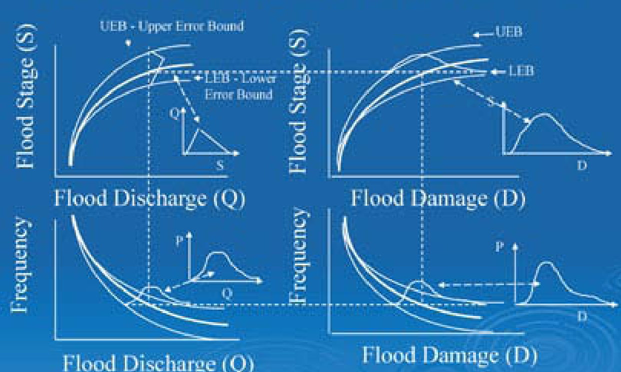
Discharge Recurrence Intervals for Different Frequency Distributions:

100-year event GEV distribution = 225-year event on LP3



Uncertainty and Flood Damage Calculation

(Corps of Engineers Procedures - HEC-FDA;1992)



CONCLUSIONS

- Flood and Drought Management are the 'leading edge' of any pragmatic adaptation strategy – both for 'managed' and rainfed systems.
- IWRM is the accepted paradigm/context for dealing with climate adaptation and adaptive management
- Transitional pragmatic economic evaluation and engineering design tools needed in absence of good information from GCMs and forecasting models
- Expansion and improvement of current hydromet monitoring systems is essential to effective climate adaptation – esp adaptive management
- Economic decision criteria dominate any adaptation responses – need to be revised
- Practicing research hydrologic engineering institutes should lead efforts in developing new transitional methods for climate uncertainty analysis for water management (planning, operations and design).

Current Methods

Current Methods for Hydrologic Frequency Analysis

Beth Faber, U.S. Army Corps of Engineers

Abstract

Management of flood risk requires estimates of the annual exceedance probability associated with large, damaging floods. Current methods to estimate flood frequency relationships use observations of the annual maximum streamflow as a sample of that probability distribution. Observations are assumed to be random and independent, and representative of the distribution of interest. For the sample to be homogeneous, the process that generates annual maximum flows must be unchanging over time, or follow a trend that is recognizable and quantifiable to allow adjustment of past observations to a present or future state. Trends due to climate change are more difficult to recognize and predict, making such adjustments more difficult, and the flood frequency relationship more uncertain.

Introduction

My assignment for this week was to discuss current methods for flood frequency analysis. I'm not going to give a complete survey of current methods, but rather just enough detail on common techniques to discuss stationarity.

This is going to be an engineer's primer on flood frequency analysis. I teach these techniques to the Corps of Engineers for use in practice, and so I make an effort to use the most straightforward language and concepts. This week, we have an audience of experts on the topic, but I'm going to follow the same approach, just to keep in mind that new techniques we develop are eventually going to be used by these same engineers working in the practice, and must be understandable at that level. This will be the same type of presentation that I use in instructing within the Corps of Engineers. I'm going to cover the basic methods of flood frequency analysis, including why and how we do frequency analysis, the assumptions that we make, the challenges to those assumptions including nonstationarity, and the ways we address those challenges.

To manage flood risk and to perform explicit flood risk analysis, we need estimates of the annual probabilities of extreme flow events, particularly those that cause damage. We need a continuous frequency relationship between flood magnitude and annual exceedance probability, a distribution, which allows us to evaluate the probability of events that have not necessarily occurred. The relationship we build should represent the current conditions and also our planning horizon. In some cases, we might expect a different relationship for the current condition than for later points in the planning horizon, requiring several different distributions. When possible, we prefer to infer these probabilities from a record of observed flows. That means we are using the past as what Bob Hirsch just referred to as an unplanned experiment to learn about future possibilities.

When we don't have a gaged flow record, we use precipitation frequency analysis with similar assumptions. From an engineering standpoint, we make the assumption that a given precipitation frequency event might lead to a flow event with the same exceedance probability, which is not necessarily a good assumption, but gives us a basis to produce the needed flow frequency relationship. Precipitation frequency analysis uses the same general principles as flow frequency analysis.

I'm going to discuss the simple techniques by starting with the simplest case – when we have a record of observed annual maximum flows. We treat this record as a random representative sample to fit our simplified statistical model, which is a single probability distribution of annual maximum flow. In order to use this model, we're assuming that the sample is IID – annual peak flows are random and independent, and identically distributed, meaning we can fit a single distribution to annual maximum flows. This assumption requires that we work with homogenous data sets to the greatest extent we can. In some cases, we adjust the data set to be homogenous, as we'll discuss later. The final, perhaps most important

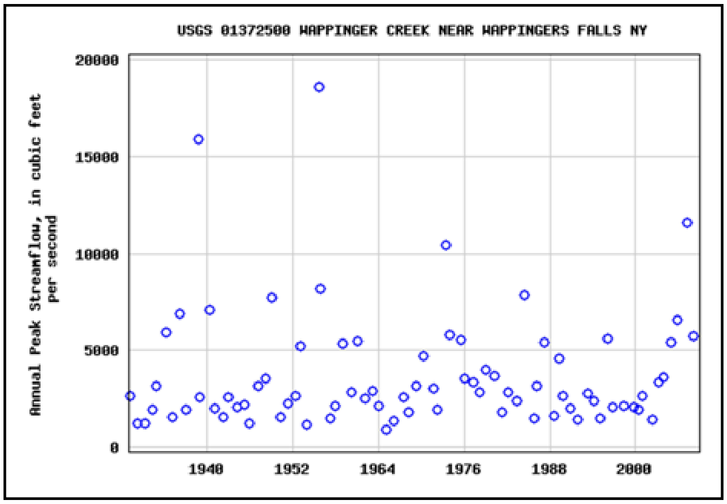


Figure 1a. Annual Peak Flow on Wappinger Creek

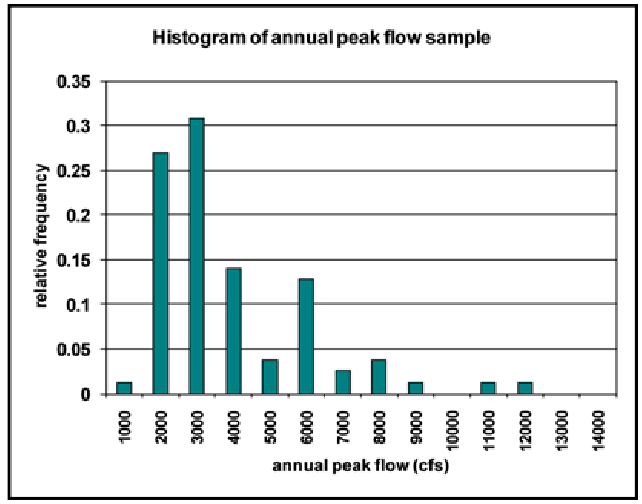


Figure 1b. Histogram of annual peak flow

assumption is that the sample is adequately representative of the population. Bob Hirsch showed us some very compelling examples of when the sample was actually not representative of the population, and it's an important point that we consider in this analysis.

Next we'll look at some data. Figure 1a is an 80-year record of Wappinger Creek, which is a tributary to the Hudson River in New York. If we're treating this as a sample from a single probability distribution of peak annual flow, we can make a histogram to take a look at the PDF. Figure 1b is quite positively skewed. In general, with annual peak flows we work with log of flow to develop a distribution that's a little bit more symmetrical (less skewed), and Figure 1c show a continuous distribution fit to the logs.

We usually display this information with cumulative probabilities. Figure 1d is the same data, with exceedance probability on the horizontal with a normal probability scale and flow on the vertical with a log scale. Each flow value is plotted against an empirical frequency estimate, meaning that the largest value in 80 years is plotted at about 1 in 80, and second largest is about 2 in 80 or 1 in 40. Rather than just use this empirical distribution, we fit a theoretical probability distribution. The reasons for fitting a theoretical relationship include getting a smooth fit to the data, a compact representation, and most importantly, to provide a reproducible method of extrapolating the upper quantiles. Our main interest is the upper quantiles, or upper tail. A theoretical distribution such as Log-Pearson Type III distribution provides a way of estimating the hundred-year event, and in cases it's needed, perhaps the 500-year event.

Flood frequency analysis in the U.S. generally refers to Bulletin 17B, the Guidelines for Determining Flood Flow Frequency. These guidelines were developed by a committee of Federal agencies between 1976 and 1982, or as early as 1967 if we consider Bulletin 15 as well. Prior to Bulletin 17B, the different agencies would develop different flood frequency estimates and recommendations that were not consistent with each other. The guidelines were intended to provide a consistent and reproducible method of developing flood quantiles. The Bulletin techniques apply to unregulated or natural flows, though in some cases we must back-calculate the natural flow in a regulated basin.

Bulletin 17B's recommendation of the Log-Pearson Type III distribution resulted from testing and analysis of several different probability distributions, also including Gumbel and Gamma, both without and with regional information. The Log-Pearson III with regional info was picked because it specifically gave the best estimate of the hundred-year flood for the data sets that were used. The Bulletin recommends estimation of the parameters from the data by the Method of Moments, using a local mean and variance, with the third moment, skew, weighted with regional information. The Bulletin also has procedures for incorporating historical flood information with a weighted-moments approach, for adjusting the distribution for low outliers in the data, and for estimating regional skew. This afternoon, we're having a panel discussion on Bulletin 17B and the fact that there's an effort to update the Bulletin with new methods for those tasks, so I'll leave further discussion until this afternoon.

Now we return to the assumptions made for our simplified statistical model of a single probability distribution for annual peak flow. We assume the annual flows are random and independent and also that they're identically distributed, meaning that they're either from, or can be treated as being from, the same probability distribution. Those annual flows must result from the same hydrologic process, or multiple processes with consistent relative frequencies. An inherent assumption,

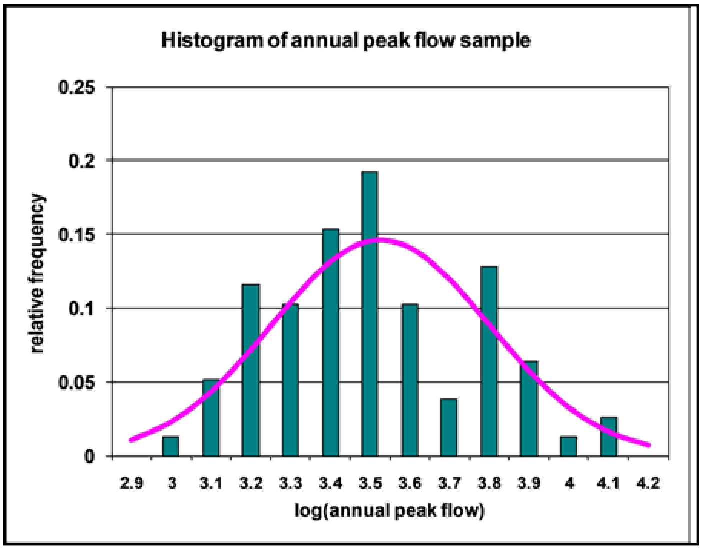


Figure 1c. Histogram of log of annual peak flow

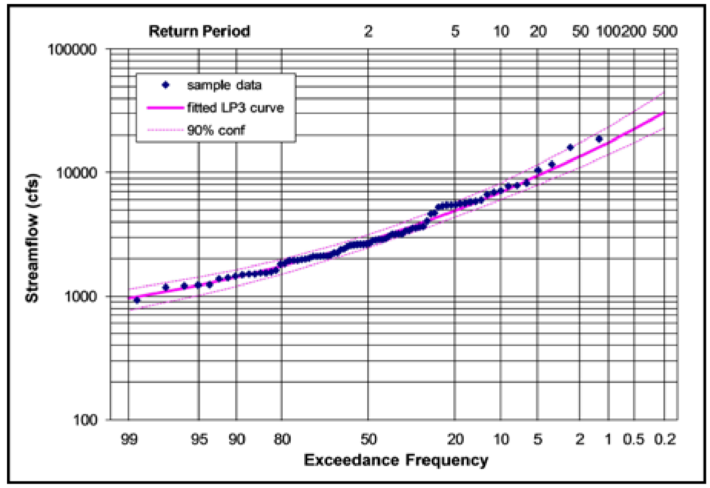


Figure 1d. Cumulative frequency curve and plotted data

because we collect data over time, is that the process must be stationary, in this case meaning unchanging or changing in a transitory or cyclic manner, where the cycle is short enough to be defined within the period of record. This assumption means we're computing long-term probabilities, which is perhaps a different probability relationship than the conditional probabilities we might compute at some point in the cycle. An example is El Nino/La Nina. A long-term frequency relationship might hold across those conditions, but if we were interested in frequency during an El Nino year, we would need a probability distribution for only that condition.

In some cases, the model assumptions such as stationarity are not true. As has been stated today, the world is obviously changing, and it has always been recognized that watersheds change over time. If the reason for the change is a physical process that can be observed and quantified, we can remove the trend or shift by adjusting the earlier events to a current condition or, in some cases, a future condition. The key is that the trend must have known cause, must be observable to be removed, and if we're interested in an estimate of future condition, the trend must be predictable. In general, for trends that we can only observe statistically, we don't have a basis for extrapolating them out to the future.

Some examples of quantifiable change are urbanization as a trend, and regulation as a shift. For urbanization, a frequency analysis will include reproducing the observed record of flood events in a rainfall-runoff model, each with the level of basin urbanization at the time it occurred, and then re-simulating all flood events with a current level of urbanization. The result is a data set that is stationary with respect to urbanization, to which we can successfully apply our simplified stationary statistical model. Figure 2a displays an example of adjustment for urbanization, where the green line is percent impervious area, the pink points are the original flow record, and the blue points are the flow record adjusted for urbanization. You'll notice that there is more relevant change in the lower flows than in the larger flows. These larger flows tend to occur on a saturated basin and therefore are less responsive to changes in impervious area. In the frequency curves in Figure 2b, the adjusted flows therefore show an increase in the low end of the curve and not in the higher, which is typical for urbanization.

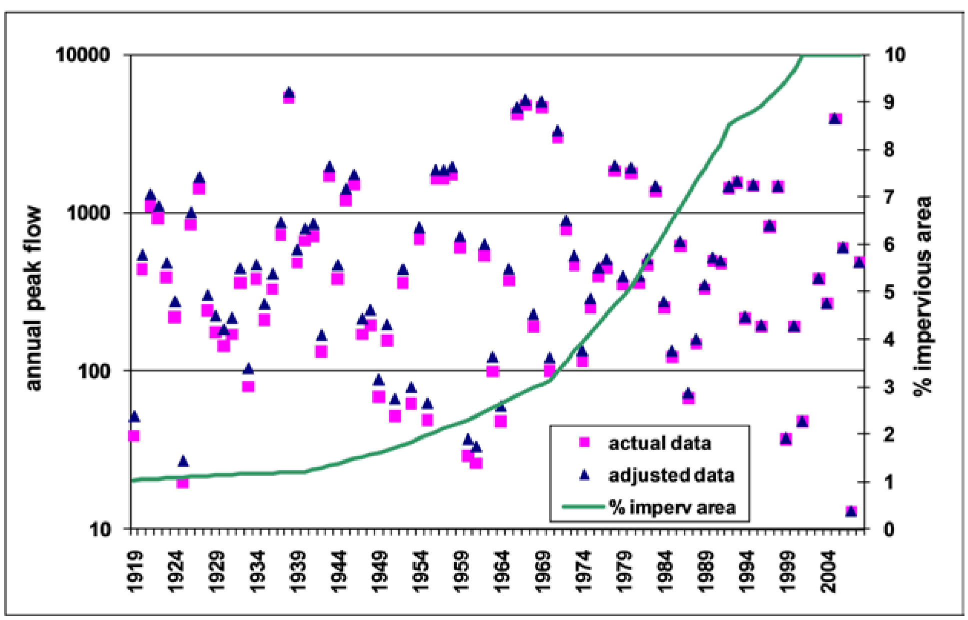


Figure 2a. Peak flows adjusted to current urbanization

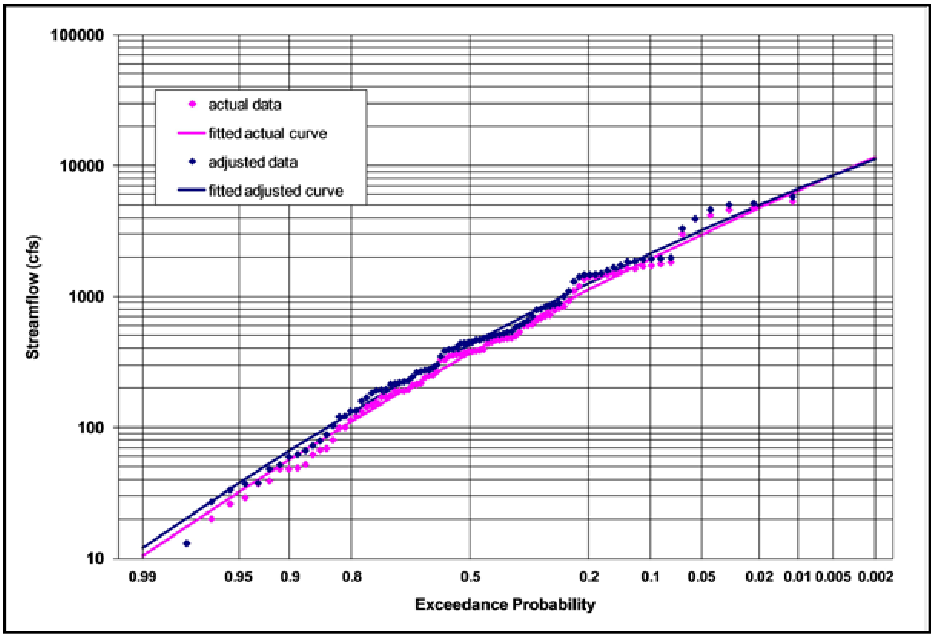


Figure 2b. Frequency analysis with peak flows adjusted for urbanization

So one might ask, if we are experiencing change, why not just work with the recent part of the data set, which we might think is more representative of the present, rather than the longer record? The reason we do not is that the greatest source of uncertainty in a frequency analysis is in inferring a distribution with a data set that is either too small or not representative of the population. Thinking back to the records that Bob Hirsch showed this morning, a limited portion of the data set implied a very different frequency relationship than the full record to date. The skew coefficient in particular is very sensitive to sampling error. Figure 3 displays a 100-year flow record, with the pink line showing the skew recomputed with each year of the increasing record, and the light green showing the 1%-chance event (the hundred-year event) from a Log-Pearson III estimate. We see that within the 100-year record, the skew estimate changes quite dramatically, with our best estimate still not stabilitized at the end. As further evidence of the uncertainty in the skew computed from a flow record, Figure 4 shows PDFs of sampling distributions for estimates of skew using various sample sizes, resulting from a Monte Carlo experiment. The variance in the skew estimate decreases with sample size, as does the bias, but both are still significant in a 100-member sample.

The next images display the uncertainty in estimates of the entire frequency curve, again using Wappinger Creek, which is a fairly well-behaved data set. The figures develop the sampling error for sample size 20. Figure 5a shows the array of distributions fit to various 20-year portions of the record, plotted around the estimate from the entire 80 years (in pink). If we instead create 20-year records by re-sampling with replacement from the 80-year record, Figure 5b adds this wider array of fitted distributions. Finally, if we randomly selected flows from the best-estimate frequency curve to create 20-member samples, Figure 5c shows this widest array of fitted distributions. This third figure captures the typical estimate of uncertainty in a frequency curve based on the sample size of the flow record. With a much larger number of random samples and fitted curves, a 90% confidence interval would span 90% of the curves at any frequency.

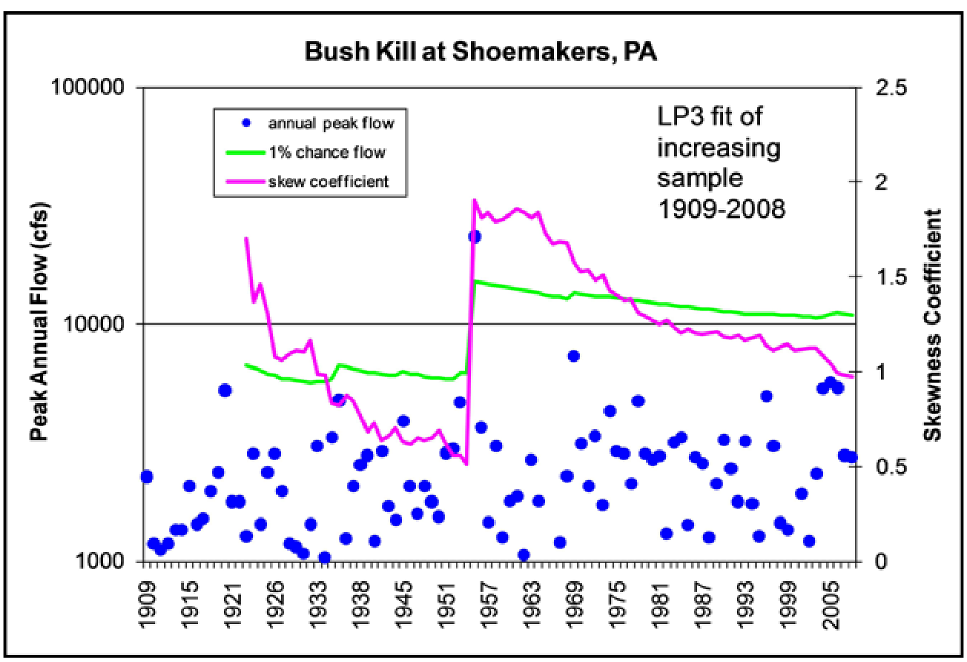


Figure 3. Skew coefficient and 1% LP3 quantile for increasing record

The figures give an image of the uncertainty in a 20-member sample from this distribution, but they can also let us see the decrease in the sampling error as the sampling size increases. Figure 5c depicts 20-year records. Figure 5d is a similar plot with 60-year records. And Figure 5e uses 100-year samples from the same distribution. We can see the decrease in error with a larger sample, and we also see the remaining uncertainty in the upper end of the curve which is of the greatest interest.

Clearly, a larger data set reduces sampling error and gives a better estimate of the frequency curve. Even without a continuous flow record, we can incorporate the important information of a longer record using the fact that extreme historical events tend to be recorded in some way, even before the existence of a gage. Thank you to Tim Cohn of USGS for the next image. Figure 6 is a newspaper record of a large event in 1907, which also mentions the even larger event from 23 years prior. The large flood flows and their estimated longer return periods give us a better idea of the upper end of the frequency curve. The estimated curve can incorporate this information using Bulletin 17B's weighted-moment algorithm or the Expected Moments Algorithm (EMA), which we'll be talking about this afternoon. With EMA, we can also use the fact that for a particular period, no large floods occurred, which is valuable information about the time series.

In addition to the historical flood records, paleoflood information is valuable evidence of the largest floods over an even longer period of record. Scars on trees and slack water deposits allow flows to be estimated, and give even more information about the extreme upper ends of the frequency curve. While the Bulletin 17B technique is not adequate for an historical period many times as long as the available continuous record, EMA has been used to incorporate paleoflood data.

Revisiting the assumptions of the simplified statistical model, we see that more data can give a better frequency estimate, but a longer record spans more time, making it more sensitive to the stationarity assumption. Another method to generate a larger data set is regionalization, in which we bring together observations from several independent sites with similar properties. The expression used to describe regionalization is "substituting space for time," because we build a larger sample across more space without spanning more time. Regionalization is a bit more straightforward for precipitation analysis than flow, because with precipitation we expect the probability distribution to be more similar from one basin to the next, while for flow the size and shape of the basin will affect the distribution. So for flow frequency analysis,

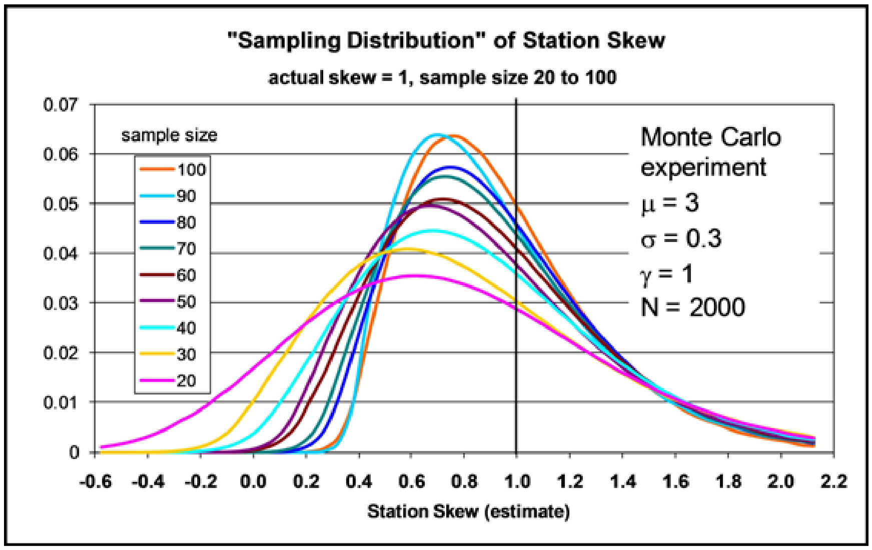


Figure 4. Sampling distributions of skew coefficient for various sample sizes

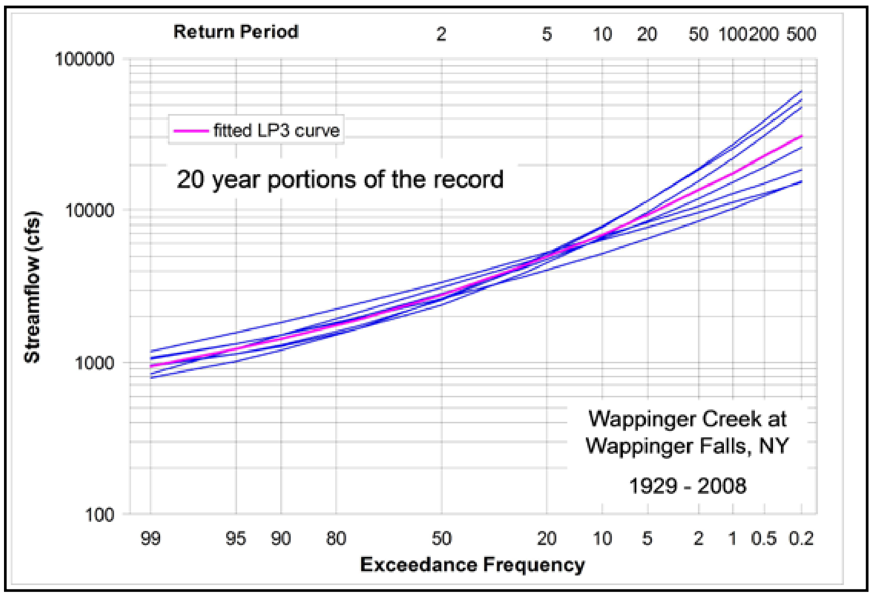


Figure 5a. Frequency curves fit to 20-year portions of an 80-year flow record

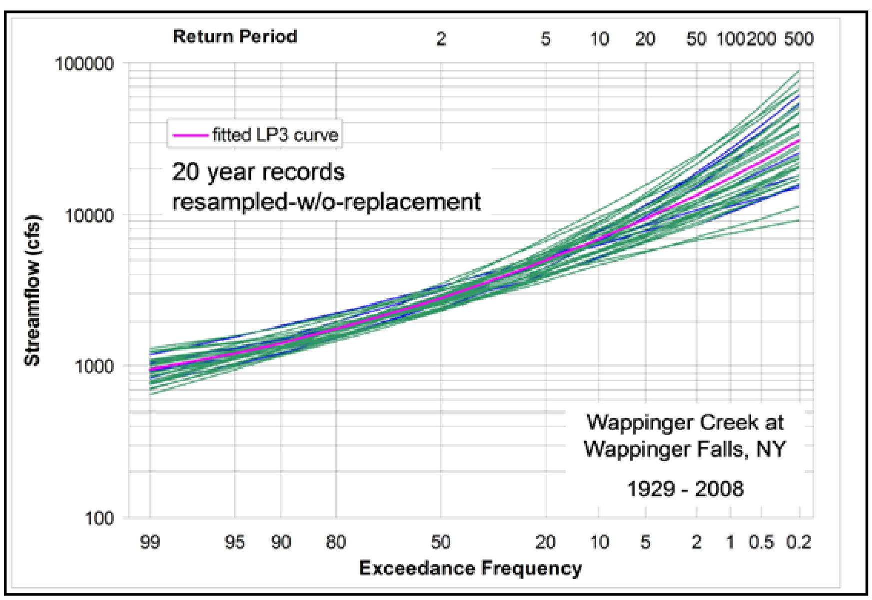


Figure 5b. Frequency curves fit to re-sampled 20-year sets from an 80-year flow record

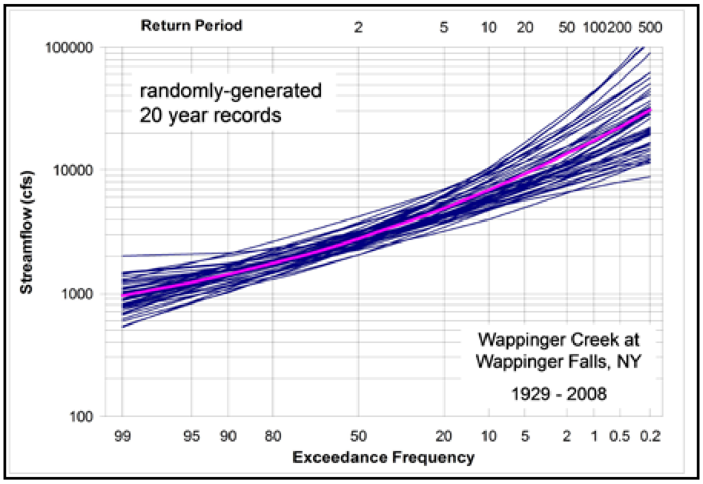


Figure 5c. Frequency curves fit to random 20-member samples from assumed frequency curve

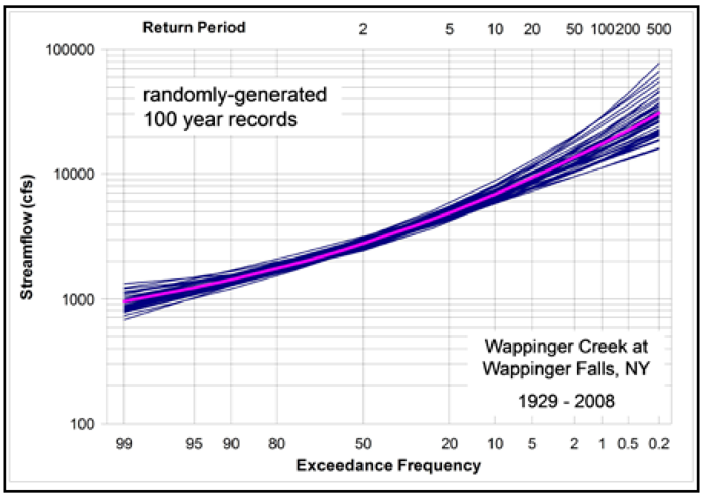


Figure 5e. Frequency curves fit to random 100-member samples from assumed frequency curve

putting together independent sites with similar properties is a little more difficult.

There are several methods for regional flow frequency analysis. The Index Flood method assumes that the probability distribution for each site is the same but varying by a scale factor, which is often the sample mean of the annual peak flows. Another approach regionalizes only dimensionless parameters like the skewness coefficient. A third uses regression analysis (Ordinary Least Squares, Generalized Least Squares) to develop a linear relationship

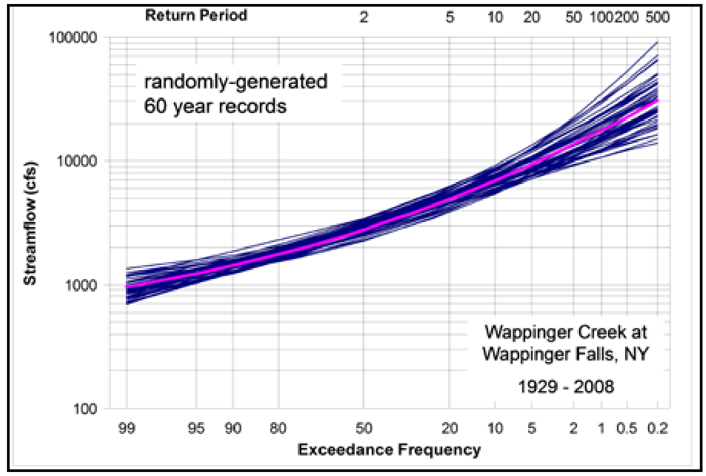


Figure 5d. Frequency curves fit to random 60-member samples from assumed frequency curve

between flood quantiles and watershed-specific parameters like drainage area, slope and forestation.

One of the challenges of the regionalization techniques is that it is difficult to put together a collection of gage sites that are independent of one another. The large events tend to span multiple sites or even an entire region, causing cross-correlation between the records and so reducing the effective size of the data set. The more recent Generalized Least Squares technique can account for that cross-correlation and also the fact that error varies from site to site due to differing sample sizes.

This has been a very basic talk on the very basic techniques, intended to discuss the fact that our simplified statistical model is sensitive to the assumption of stationarity. But when we can recognize trends, we can remove the effects of various types of nonstationarity like urbanization and regulation. Some techniques that improve the frequency estimates, such as incorporating historical information, are even more sensitive to the assumption of stationarity. Regionalization can help improve frequency estimate while spanning less time, but has problems of its own with correlation. The rest of this week will introduce and discuss the much more sophisticated techniques in frequency analysis and climate modeling. Hopefully, I've set some groundwork to let us jump off. Thank you.

"...The worst flood since the memorable 1884 flood now holds sway in the Ohio valley. A new high water record has been established in Pittsburg, and though the mark of '84 was not passed at Wheeling the second flood stage to that destructive water will be attained here this morning. .."
--***The Intelligencer****, March 15, 1907, p. 1*

Figure 6. Newspaper record of 1907 flood event

Biography

Beth Faber has been with the Hydrologic Engineering Center of the Corps of Engineers for 10 years. Her work focuses on flood frequency analysis and risk management, multi-purpose reservoir operation using forecast information, water supply yield analysis, and reservoir optimization. Prior to the Corps of Engineers, she worked in reservoir operation at Denver Water. Beth's BS and MS are from the University of Colorado at Boulder, and her PhD is from Cornell University in 1999.

Current Methods for Water Resource Planning

Rolf Olsen, U.S. Army Corps of Engineers, Institute for Water Resources

I am going to describe current U.S. water resources planning requirements and how hydrologic frequency information and climate information are included in the decision-making process. The goal is to describe how current laws and regulations influence the use of climate information.

Before I start, I'm going to do an advertisement for Circular 1331, published by the USGS, written by four federal agencies: the two primary federal water resources management agencies, the Army Corps of Engineers and the Bureau of Reclamation; and the two primary water science agencies, USGS and NOAA. You can download it online at http://pubs.usgs.gov/circ/1331. A lot of the topics at this workshop were framed based on what we wrote in this report.

This talk will be about some of the guidance that we have for making water resources planning decisions. I will provide a foundation for some of the things that Gene Stakhiv discussed, such as the Economic and Environmental Principles and Guidelines for Water and Related Land Resources Implementation Studies (P&G). Gene also talked about hydrologic design standards, such as the standard project flood. There are other laws that influence water resources decision-making. One is the National Environmental Policy Act (NEPA). A big driver for floodplain management is the National Flood Insurance Program (NFIP). I will also talk a little bit about risk and uncertainty analysis.

Both Gene Stakhiv and Jerry Webb said that these regulations are in place. But the new Administration and the Council on Environmental Quality are currently revising these regulations. So I'll talk a little bit about what the proposed revisions are and if they are actually improvements for climate adaptation or might be a hindrance.

There are a lot of international perspectives at this meeting. Although I will be discussing U.S. federal laws and regulations, these issues apply to water managers everywhere. The questions are: how do you make decisions balancing competing, multiple objectives; how do you trade off benefits with economic costs; how do you consider environmental constraints in planning; what is a standards-based approach to risk? So the talk does have a much broader perspective, even though it is from a U.S. Federal perspective.

The 1983 economic and environmental principles and guidelines, or P&G, says "the federal objective of water and related land resources project planning is to contribute to national economic development consistent with protecting the nation's environment, pursuant to national environmental statutes." One alternative plan that must be considered is the alternative with the greatest net economic development (the NED plan) consistent with protecting the nation's environment. However, this plan does not have to be chosen. There may be overriding reasons for recommending another plan, based on other federal, state, local and international concerns. So the general approach of the P&G is economic optimization, maximization of economic benefits and minimization of costs, subject to environmental constraints although there can be exceptions.

The proposed changes to the principles and guidelines emphasize more of a multi-objective approach. The objective is not only to maximize net economic benefits, but also environmental benefits, social benefits, and public safety. The approach is to optimize economic, environmental, and social benefits.

As Gene Stakhiv and Beth Faber mentioned, we need to estimate the future probabilities of hydrologic events that are used to calculate this future stream of benefits for different alternative action plans. There is nothing really in the P&G that says we have to use a stationary model. If nonstationary models existed, they could be applied to economic decision-making.

An alternative method for hydrologic design is a standards-based approach. For example, a standard project flood (SPF) is a flood "that may be expected from the most severe combination of meteorologic and hydrologic conditions that are reasonably characteristic of the geographical region involved, excluding extremely rare combinations." There was discussion in the Corps of Engineers a few years ago about whether they should rescind the guidelines on use of a standard project flood. Discussions with experienced water managers indicated they did not want to rescind it. The SPF was often used as a design standard in the mid-20th century when flow records were considered to be too short for adequate statistical analysis. It is an approach that does not necessarily need a statistical model for design. Gerry Galloway is here at this workshop. He has maintained that the SPF is a good design standard for urban levees.

Another design standard is the Probable Maximum Flood (PMF), and it provides an even more conservative design. Large dams in the United States base the spillway design flood on the PMF. The probable maximum precipitation (PMP) is the maximum conceivable precipitation from a combination of unfavorable meteorological events. The PMF inflow hydrograph is estimated by locating the PMP over the watershed to produce a maximum flood response.

Gene Stakhiv equates the PMF to the precautionary principle; you do not want any failure regardless of economic costs. So these are non-statistical methods which are still on the books.

A different way to make decisions is the National Environmental Policy Act process, which requires that Federal agencies lay out different alternatives and show which alternatives could minimize adverse impacts on the environment. This is a different approach that does not require a trade-off analysis like the principles and guidelines. When we were writing Circular 1331, we had a lot of discussion about how to do planning. The individuals from the Bureau of Reclamation were thinking of planning in terms of the NEPA process, where you do not need a tradeoff analysis and therefore do not need probability distributions for the calculation of future economic benefits and costs. On the other hand, the P&G require a tradeoff and benefit-cost analysis that require the probabilities of future hydrologic events. So when you hear these presentations, you have to think about the actual decision process that people are trying to follow.

So it brings us to the National Flood Insurance Program. The National Flood Insurance Program requires delineating a special flood hazard area, which is the area of land that would be inundated by a flood having a 1% chance of occurring in any given year (also referred to as the base flood or the 100-year flood). Flood insurance must be purchased if federal loans or grants were used to acquire or build the structures or if the mortgages are made by lending institutions regulated by the federal government. Local communities have to regulate floodplain development. NFIP is a big driver for the Federal Emergency Management Agency and for the Corps of Engineers. Why is it necessary to consider the National Flood Insurance Program when discussing Federal water resources planning? Because the flood insurance program puts a lot of constraints on the local communities, and actually, the local communities, rather than seeing this as an opportunity to use flood insurance to reduce its potential risk, they see it as a hindrance to development and enhancing their tax base. So NFIP is a big driver for local communities and has become a de facto standard for flood risk management. Local communities may consider structural flood reduction projects to avoid NFIP regulations. They may work as local partners with the Corps of Engineers to develop flood risk reduction projects.

To recap, there are two types of decision and design methods. One is an optimization approach that considers either multiple objectives or only economic development. Another is a standards-based approach. For a standards-based approach, the standard project flood and probable maximum flood are more conservative standards. The 1-percent chance flood has become a de facto standard for local floodplain planning. It is not a very conservative standard; there is about a 26 percent probability of at least one flood during the lifetime of a 30-year mortgage. The SPF and PMF are not necessarily statistically based standards. On the other hand, the 1-percent chance flood requires flood frequency estimates.

There is guidance on how to address risk and uncertainty. The principles and guidelines say planners shall identify areas of risk and uncertainty in their analysis and describe them clearly. Climate change and future climate variability add additional uncertainty. Probability distributions can be used if there is reasonably firm data. The P&G allow the use of subjective probability estimates to characterize future outcomes. The P&G recommends using a sensitivity analysis to evaluate what the impacts of uncertainties are on your decision.

Some people, Gene Stakhiv being one of them, have argued that the principles and guidelines are flexible enough to accommodate planning for climate change, but there are some aspects of the P&G which may hinder planning for climate change. One of these is the requirement to base evaluations of alternative plans on the most likely future conditions. So what does that mean with climate change? How are we going to characterize the most likely future conditions? In addition, the P&G generally employ a decision methodology that requires an optimization approach.

The Council on Environmental Quality released proposed revisions to the P&G in December 2009. They are out for public review, and there is going to be a National Academy of Science panel to review them. Probably some of the people in this room will be on that panel. So I'll talk about how they affect planning with climate change.

The 1983 P&G use a six step planning process: (1) specify the problem, (2) inventory, forecast, analyze conditions, (3) formulate plans, (4) evaluate effective plans, (5) compare plans, (6) select a plan. I am going to highlight a couple of things in the revision that I think have implications for climate change adaptation. The revision emphasizes even more the requirement to determine the most likely future water and related resources conditions.

In the past, the Corps got criticized for the Upper Mississippi River navigation study for picking a most likely future condition which gave a lot of benefits for navigation in the future. It was criticized because there is really very little certainty that this would be the actual future. The Corps was then compelled to take a scenario approach where they looked at several different possible futures. The proposed revised P&G, once again, emphasize using the most likely future condition. The evaluation of reasonable and viable alternatives is made relative to the most likely conditions without action.

The proposed revision explicitly says to address climate change. The document says, "From specification of existing problems and opportunities to the formulation, evaluation and selection of plans, the accelerating changes in aquatic systems caused by a changing climate should inform our understanding of what our water resource needs are and how we can realistically respond to those needs."

The proposed revision also discusses risk and uncertainty. Everybody will likely agree with this statement in the revision: "Even with the best available engineering and science, risk and uncertainty will, of course, always remain." But if you continue reading, the document says when there are uncertainties about an alternative's ability to function as desired, "improved data, models and analyses should be pursued." So that is great for the research community, but how are you going to do this to make actual decisions? You just keep analyzing the models for 20 years until the future climate uncertainty is reduced? The guidance is ambiguous.

The revision also provides guidance on scenarios. It says scenarios shall only be used as sensitivity tests to assess the robustness of competing alternatives. The document also says to present the probability or likelihood of each future condition and its effects. Are we going to actually assign probabilities to conditions and if so, how do we do it? So that is what this conference is about. The proposed revised P&G continues using an optimization approach. Hopefully this workshop will present alternative decision-making methodologies. It may be better to consider a broad range of scenarios without necessarily assigning probabilities, and use scenarios in ways besides only sensitivity analysis. These topics will be discussed later in the workshop.

In conclusion, there are two methods that are currently driving water resources planning and that require estimates of the probability of future hydrologic events. Multi-objective and economic optimization assumes "a most likely future condition" and characterizes future hydrologic events with a probability distribution. Delineation of flood hazard areas is based on flood frequency estimates that currently assume stationarity and do not take into account the uncertainty in the flood frequency estimates. The objective of this workshop is to consider if there are better approaches that would help us deal with future hydrologic uncertainty and climate change adaptation.

Biography

J. Rolf Olsen is a water resources systems engineer with the U.S. Army Corps of Engineers (USACE) Institute for Water Resources (IWR) in Alexandria, Virginia. He is currently managing a new program on USACE Responses to Climate Change. He has led a number of studies involving climate change and water resources, including an analysis of the implications of climate change and variability on flood frequency analysis for the Upper Mississippi River System Flow Frequency Study and an evaluation of potential climate change impacts on inland navigation for the Department of Transportation. He has a Ph.D. in Systems Engineering from the University of Virginia, a master's degree from the Pennsylvania State University and a bachelor's degree from Columbia University. He was a nuclear submarine officer in the U.S. Navy for eight years.

Nonstationarity and Water Management

Nonstationarity and Dam Safety

Nate Snorteland, U.S. Army Corps of Engineers

Abstract

Modern concrete was invented in the late 1800's, but it bears little resemblance to concrete produced today. Throughout the early 20th century, concrete was refined and re-engineered as more was learned about how it behaved under years of tensile, temperature, and abrasive loading. The advancement of concrete dam technology proceeded at a similar pace, roughly following the advancement of its main constituent. Dam design changed after the failure of Malpasset Dam in 1959 and following the failure of Vaiont Dam in 1960 when the importance of site geology and regional geology became apparent. Dam design changed significantly after the near failures of Koyna Dam in 1967 and Lower San Fernando Dam in 1972 when understanding the importance of the performance of dams in earthquakes became apparent. Embankment dam design changed even further following the failure of Teton Dam in 1976 where the importance of filters was tragically highlighted. The history of seismology was written mainly following some of the major seismic events and accompanying disasters from the 1906 San Francisco Earthquake through the 1995 Kobe Earthquake. After each event, the analysis tools, the understanding of the nature of the events, and the methods used to evaluate seismic risk underwent major updates. Each of these disciplines has been forced to consider nonstationarity as a consequence of the limits of human knowledge of natural systems. Although not an exact comparison, what the hydrometeorology profession is experiencing related to climate change is similar to the experience in seismology over the last 100 years and what every profession has experienced as our understanding of the world around us has advanced. The climate changes, crustal plates move, and human understanding changes and adapts. As the science surrounding climate change advances, it will be absorbed and assimilated into standard engineering practice. This paper briefly summarizes how dam safety considers or plans to consider the changing climate into its evaluation of the safety of its structures.

Presentation

I am going to have a short and sweet presentation, because I do not have a lot to tell you guys about climate change. But I had some questions, and I guess every time I hear climate change, I check in every couple months and see what the industry is doing and see all the fancy graphics that you guys generate. Right now, you guys are leading the industry in color graphics that seem like there's a lot of fancy stuff here. Then I come to these workshops, and people say I don't really know what we're doing. So I don't know what's going on between the two things.

So I am going to talk a little bit about change. I'm going to pose some questions, and I'm going to kind of cover change in other technologies that affect dam safety that are similar to what's going on in hydrology with respect to climate change, including concrete dam embankment, seismology. I will talk a little bit about hydrology, but it will be short, because like I said, I'm not the one to talk to you guys about hydrology. I'll talk somewhat about the challenges and then propose some answers to a very limited set of the questions I'm posing.

So I hate to admit that every time I go to one of these, I have to look up what non-stationarity means, and that always comes back, things change over time. The good news is that humans, and even engineers, adapt to changes over time, even though they do not seem to like it. What we do are loads and design standards, analysis methods, and consequences. Most recently, dealing with consequences has not been a traditional concern of engineers. However, unlike some of the science professions, most of our changes are the result of some disaster, and so that is how our profession changes a lot. I see a lot of excitement going on in the climate change community, and I'm glad to see it. It doesn't cause as much fear in me as when changes happen in the engineering community, because it usually means that many people lost their life in order to have some change in the engineering community.

So you probably see 40 or 50 or 60 or a hundred of these fancy charts, and they all have time on one axis. I am not going to try and explain them all, but there are a lot of crazy-looking things, like this chart. It looks like we should be on fire. I don't want to minimize the dramatic nature of climate change, but it always kinds of amuses me to see some of the alarming things that are going on, and honestly, because I feel like the whole engineering community does a very good job of trying to assimilate change and assimilate different states of nature and different understandings of nature into their analyses.

So when we talk about dams there are questions we have, and one of the biggest questions, does climate change affect reservoir operations? So does climate change affect safety? Does climate change affect frequent or infrequent events, or both? Is it cost-effective to address deficiencies related to climate change?

One of the things that I think of when I say climate change is most of the things that happen bad to dams and levees happen far below their design level or their design elevation. So those are the things that keep me up at night. I think some of the things that happen with climate change and some of the more infrequent hydrologic events, those things don't keep me up as much. If something happens suddenly in the middle of the night, it only happens in an unexpected way. This doesn't mean we don't do things, because we do a lot of modifications to dam safety to address hydrologic issues. But we need to ask, do safety decisions need to consider climate change, given the frequency of decisions. I will go over the frequency that we make decisions about dams.

One thing that would be nice to know is, how does climate change affect an agency's perception about its portfolio? Is it regional? Does it affect all of my 600 dams and 900 structures and dams? Does it affect certain basins? All of these things would be important to the decision makers as you're trying to figure out, is my risk portfolio higher across the board than I thought or is it lower across the board than I thought? Those are the kinds of things that would be nice to know, going forward, and is it an emergency? And those are part of the things that we do in dam safety to manage a host of emergencies. It would be nice to know if some of the things in climate change are emergencies.

I am only going to touch on levees, because that just opens a can of worms I don't think we ought to go into today. But there are some important questions, and one is that, does climate change affect river flows? Because river flows are where it's at for risk for levees. Will medium-sized floods become more frequent, because levees are designed for about a 100-year or 500-year level? That is a pretty frequent flood for what we usually consider to be risky for dams. So if there are climate change phenomena that affect medium-sized floods in that range, it would be nice to know. And it goes from planning all the way through safety evaluations. And then does the change in climate affect the duration of flooding? Because the duration of flooding also affects the safety of levees. It is not just one peak level that affects the safety.

I am going to go over some of the things that happened in the dam safety community that are similar to what is going on with climate change. And really, it's nice to see that the hydrologic community is adapting to change. I would be concerned if you guys were seeing all these climate things and said, we don't know what to do. We're just going to ignore this. It's an anomaly.

Concrete technology is a little bit similar, in that people have been using concrete or some form of concrete since the late 1800s. The concrete that was put in during the late 1800s and early 1900s, after 20 years, they learned some important lessons about it, and that is, performance changed over time, and it wasn't strong, and didn't like the cold, and they had performance anomalies like alkali-aggregate reaction. The good news is, there weren't many disasters, but it degraded in performance, it degraded and fell apart and slowly broke down.

It led to pretty phenomenal advances in the 1930s, '40s, and '50s, like air entrapment, low alkali cement, low heat of hydration cement, et cetera. The concrete you see in your driveway today is actually a modern miracle of technology, with little air bubbles to keep from freezing and thawing and low alkali cement to keep sulfates from attacking it. There are all kinds of stuff in there. The point being is that as they noticed the performance of the structures changing over time, they tried to adapt the science, and especially in cement technology, to accommodate for that.

Concrete dams, a subset of that concrete technology, changed as a result of some fairly significant disasters. Failures included St. Francis Dam in 1928 (top right on slide), Malpasset Dam in France, down in 1959, and Vaiont Dam, which actually was a landslide. You can see the landslide there on the bottom left. What we learned in St. Francis is that uplift pressures are really important. That is water you see coming out of the dam there, there is no drain in the dam, and that contributed to the failure. They failed to take into account the geology and left abutment, and it failed about four years after first filling. In Vaiont Dam, which was a very significant life loss disaster, they failed to account for the landslide that eventually turned into a saturation that topped the dam and wiped out two towns in Italy.

The significant disasters have changed how we think about things, and we think about geology a lot now when we look at concrete dams. We think about drains a lot. We think about a lot of the performance things that we didn't back in the early '40s and '30s when we were designing concrete dams. On the right there, you see Lower San Fernando. I didn't have a picture of Hebgen. Water made it over the top but it didn't fail. And then Teton Dam.

What we learned from Lower San Fernando Dam is that earthquakes are important. They can really affect structures. Back in the '40s, I think, is when Lower San Fernando Dam was actually designed and built. They didn't really think about those things. They weren't in the forefront of how we look at this stuff. I'll go to seismology a little bit to explain that a little bit further, but what we learned in Lower San Fernando has dramatically affected how we analyze embankment dams. In Teton Dam, we learned a couple of important lessons. One is that geology and embankment have to be really compatible, and filters are incredibly important. You won't see an embankment dam built without a filter, and Teton Dam is primarily the cause of that.

So states of nature change, which is what climate change appears to be. Sometimes it's more our understanding of what nature really is doing that changes over time. But either way, that safety matters, we try and adapt our state of knowledge about the structures. I think seismology is probably more similar to hydrology than anything else I'm talking about, and right now, here are plate tectonics, and I am not going to ask you to calculate that 356 million year flood. But the point being that seismology changes over time. Plates drift. There's plate tectonic theory I'll get to in just a second. And that is one of those things that also change over time, although I think it's a little more slowly than what you're looking at for climate changing. And you've probably seen this, the ring of fire on the planet. Plate tectonic theory leads to a lot of earthquakes.

This is a brief history of seismology. I am not going to spend too much time on it, but it starts out with Hooke's Law, stress and strain, P and S waves, seismographs, the first seismograph in the late 1800s. And then there were a couple of events. The 1906 San Francisco earthquake, the 1922 Tokyo earthquake, the Richter scale invented in the '30s. The nuclear tests had a big effect in the 1960s. They discovered the earth's core and the velocities that were distributed, figuring out where earthquakes are. That's how they're able to triangulate earthquakes, because they know the velocities through the three layers of the earth. Basically, seismology is an understanding of natural events, over time, accumulated, and as they've done that, a lot of important advances have led to the things that we have today, like shake mats. If large earthquakes happen in any part of the world, or even specifically where the USGS has monitoring, we learn things. They adapt.

Most recently, after doing a bunch of LIDAR surveys in the Northwest, they significantly increased the seismic hazard that everybody uses for design, because of the Cascades reduction and some of the surface faults they found there. So there's a lot of change going on in seismology which we use for loading as well. Very similar to how we use hydrologic loading. And hydrology, I have question marks there. It's because some of this needs to be vetted a little bit better. And some of this is when we look at climate change, we're updating flood frequencies, do we update Probable Maximum Precipitation, do we use a full record or only use recent history?

These are some of the things that I think need to be communicated to managers and decision makers as we move forward, because I believe there's much judgment involved, and it's the judgment that's important for the decision makers about why it is you're choosing to go down a certain path, whether climate change is important in some cases but not in others, or whether it's considered in some cases but not others. Because it's important to our processes. Whether you are FERC or Reclamation or the Corps or even the states, there are periodic assessments of a structure's performance, and the Corps calls it periodic assessment. Reclamation calls it a comprehensive facility review. The FERC calls it a Part 12 review. They happen every five to six years.

What it means is that every five to six years, we screen each of our structures for changes for non-stationarity, if you're a scientist, and we make some sort of safety assessment of that structure. And so every five or six years, we're able to assimilate new information in this, and I will say that updated hydrology and updated seismology are two pieces of information we traditionally will include in it. At least in the seismology community, that happens a lot. Seismic activity changes a lot over two cycles or three cycles of these assessments. We are used to it, and it is okay. It's helpful to know why things change, and it's helpful to know the basis that's behind it, and sometimes, whether or not it's a consensus view or not.

Because then if we determine that it might be an issue for a structure, if it might cause our assessment to change, we do a more intensive risk assessment where we do all kinds of fancy expensive things and fancy hydrologic studies and seismologic studies and other studies where we try and get to a better decision. So any input you can have into that better decision is greatly appreciated; and climate change, I think, is one of those things that can be assimilated fairly easily into the overall process.

I think as we go forward, there's challenges that come to the front, and one is, I get the general sense that there is going to be an increasing push to change reservoir operations to compensate for changing basins. And it's not just in California, although I'd say California is probably picked as a subject quite a bit. What is important for the safety part of the organization is, we need to ensure that when we change operations to account for water management, we are trying to store more water, usually, and change operations to make sure that they do not affect the safety at the same time.

It doesn't necessarily affect what you do, but it's helpful to know what it is that the climate change is affecting, so that we can assess the safety of the structure, with the overall goal of informing the decision-maker of the basis of the decisions that they're making on these five- to six- to ten-year schedules that involve climate change. Then the answers. And this is pretty short. For dam safety, I'd say climate changes are usually well within the existing operating ranges of what our reservoirs can handle. I mean, unless it's affecting the frequency of extreme events, which actually do affect the risk and will affect some of our ability to pass floods, especially for the Corps, I would say that we're probably going to be able to handle whatever climate change has to offer.

That doesn't account for the water management side of the house, but at least for the safety side of the house, I don't feel like climate change is a huge threat to the safety of the structures, unless it's a regional or global or something that totally changes the risk profile of all the structures. As the effects become more pronounced, and some of the data suggests that it is, they'll be periodically assessed, along with the other risks that happen, by incorporating that knowledge into the frequency calculation. All those risks get compared to other risks, get compared to risks below the normal operating conditions. Gets compared to a lot of changes.

Because change is significant, because change of the operation may be significant, making sure that safety is considered when compensating for climate change is crucial. I think we'd be fools not to consider it, and we'd be happy to do it. We've always encouraged people to have more and to give us more information about why things change. But change happens all the time. It happens in every part of our world. Our existing analysis tools, once you guys are done with your stuff, I think are sufficient to ensure safe operation at this point. I don't think we need to adapt our whole philosophy to incorporate what hydrology is doing right now. That could change in the future, too.

NOTE: *This is a transcript of the author's remarks at the workshop that has not been reviewed or edited by the author.*

Biography

Nate Snorteland has a B.S. in Civil Engineering from the University of Colorado and a M.S. in Geotechnical Engineering from Virginia Tech. He has with the Bureau of Reclamation for 13 years working in materials science, construction management, geotechnical engineering, risk analysis, and risk management. He was most recently the program manager for risk management for the Dam Safety Office in Denver, CO responsible for risk management, research and development, and special issues. He is currently the director of the Risk Management Center for the U.S. Army Corps of Engineers, responsible for managing risks across the Corps' portfolio of dams and levees.

Change

- Change Over Time = Non-Stationarity
- Humans (even engineers) adapt to changes over time
  - Loads
  - Design Standards
  - Analysis Methods
  - Consequences
- Significant changes in engineering are usually a result of disasters

BUILDING STRONG®

Questions (For Dams)

- Does climate change affect reservoir operations?
- Does climate change affect safety?
- Does climate change affect frequent events or infrequent events or both?
- Is it cost effective to address deficiencies related to climate change?
- Do safety decisions need to consider climate change given the frequency of the decisions?
- How does it affect an agency's perceptions about it's portfolio?
- Is it an emergency?

BUILDING STRONG®

Questions (For Levees)

- Does climate change affect river flows?
- Do medium-sized floods become more frequent?
- Does climate change affect duration?

BUILDING STRONG®

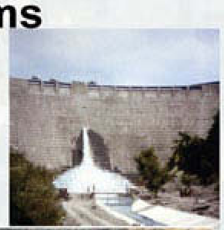
Concrete Technology

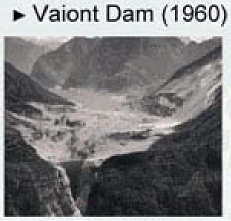
- The Early Years (1885-1930)
  - Not durable – performance changed over time
  - Not strong
  - Didn't like the cold
  - "Performance Anomalies"
- No disasters, but poor long-term performance
- Led to air entrainment, low alkali cement, low heat of hydration cement, etc.

BUILDING STRONG®

Concrete Dams

- Significant Disasters:
  - St. Francis Dam (1928)
  - Malpasset Dam (1959)
  - Vaiont Dam (1960)





BUILDING STRONG®

Processes

- Periodic Assessments / Comprehensive Facility Reviews / Part 12 Reviews
  - Every 5 or 6 years
  - Used to screen for changes (non-stationarity if you're a scientist) and make decisions
- More Intensive Assessments
  - Risk-based approaches
  - Hydrologic and hydraulic modeling
  - Decisions!

BUILDING STRONG®

Challenges

- Increasing push to change reservoir operations to compensate for changing basin conditions (not just California)
- Ensuring changing operations don't affect safety
- Informing decision-makers about the basis for safety decisions that involve climate change

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Answers

- For dam safety, climate changes are usually well within the existing operating ranges
- As the effects become more pronounced, they will be periodically assessed along with other risks by incorporating knowledge into frequency calculations
- Because changes to operations may be significant, making sure safety is considered when compensating for climate change is critical
- Existing analysis tools (post-meterology) are sufficient to ensure safe operation

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Red River of the North Flood Frequency Estimation

Pat Foley, U.S. Army Corps of Engineers

Abstract

For the last few decades the Fargo, North Dakota, and Moorhead, Minnesota, area has had to fight Red River of the North floods with regularity, culminating in the flood of record in spring 2009. Only heroic efforts by flood fighters during weeks of adverse conditions prevented a catastrophe. The St. Paul District of Corps of Engineers is currently working with the local communities to develop reliable flood protection. One of the first tasks for the flood risk management study is to determine the probability of future floods. This evaluation is used for the economic analysis of the project and to determine its reliability. The Corps standard practice is to assume historic floods provide an accurate representation of future flood probabilities, i.e. stationarity and no impact from climate change is assumed. However, a plot of the period-of-record natural annual maximum mean daily flows at the Fargo gage showed the an obvious upward trend. The 50-yr moving average of natural annual maximum flows increases from about 3400 cfs in 1950 to currently over 8000 cfs.

Presentation

The Fargo-Moorhead flood risk study is on a fast track with selection of the flood reduction measure due by January, 2010. The short time frame for the study did not allow a reliable, detailed study of reasons for increasing flood flows and an analytical evaluation of how flood flows will change in the future. The St. Paul District proposed doing an Expert Opinion Elicitation, EOE, to help the project delivery team decide how to properly address future flood risks. The local sponsors and Corps headquarters agreed with the use of an EOE. The EOE was held September 28-29, 2009, in Minneapolis, Minnesota. The official panel members were: Bob Hirsch, USGS; Dave Raff, Bureau of Reclamation; Scott Dummer, NWS; Skip Vecchia, USGS; Rolf Olsen, Corps of Engineers: and Mike Deering, Corps of Engineers, and the EOE was facilitated by Dr. David Ford of Ford Engineering. The experts addressed the following basic question: What specific actions, if any, should the Corps take to account for future climate uncertainty in the quantification of flood risk for Fargo, ND-Moorhead, MN?

The experts fairly quickly agreed that there was too much uncertainty in climate change impacts on flood flows to provide a recommendation on how to accommodate climate change in the flood risk management study. However, the experts did reach agreement that the Red River of the North at Fargo flood peak record was non-stationary and that the river has recently experienced a wet period. Tree ring studies have shown that the Red River basin has alternated between wet and dry periods for several hundred years. A paper by Gabriele Villarini and others had shown that the Red River at Fargo met statistical tests for nonstationarity with a break in the record in 1941. The panel recommended that the Corps include the impact of nonstationarity in its flood risk study. The panel did not make specific recommendations on how to incorporate nonstationarity.

The St. Paul District contracted with the Corps Hydrologic Engineering Center, HEC, in Davis, CA, to develop specific guidance on how to incorporate nonstationarity. HEC was also asked to review and evaluate how upstream reservoirs and floodplain storage impact flood peaks at Fargo. Dr. Beth Faber at HEC recommended the St. Paul District use the 1941-2009 records (wet period) to develop the current, year 0, discharge-frequency curve. For year 50, it's far enough out that HEC said there was no way of knowing which condition would be correct, so they recommended using long-term probabilities based on how much of the observed record was wet, and how much dry. This gave 65% chance wet, 35% chance dry. For year 25, HEC chose a reasonable transition between the current 100% chance wet, and the future 65% chance wet. For year 25 HEC recommended assuming an 80% chance wet and 20% chance dry. The dry period frequency curve was based on the 1902-1940 Fargo records. HEC also recommended using the skew coefficient from the Fargo records. The previous Fargo curve has used the longer record Grand Forks station for the regional skew.

As of 3 January 2010 the St. Paul District and HEC are still coordinating on how to accurately incorporate the impact of upstream reservoirs and floodplain storage on the Fargo discharge-frequency curve, so the exact impact of nonstationarity on the final Fargo flood values has not been completed. However, comparing the previous natural flood frequency curve using the full period of record with the new wet period curve based on 1941-2009, the mean of the logarithms of the annual peaks increased while the standard deviation of the logs of the peaks decreased. The results are a wet period natural frequency curve that is higher than the total period curve for intermediate floods but lower for very large floods like the 0.2%, 500-yr, flood. The wet period flood frequency curve provides a better fit to plots of the recent large floods.

The St. Paul District also compared results of a study of the impact of predicted future climate change on the discharge frequency curve for the James River at Jamestown, ND, done by Dave Raff and others. The James River study found that the Jamestown 100-yr discharge would likely increase significantly over the next 100 years. Jamestown is about 90 miles west of Fargo and the IPCC precipitation and temperature predictions are very similar. However, the James River flows south and the Jamestown drainage area is north of the city while the Red River flows north and its drainage area is south of the city. Direction of flow is important in snow melt flooding and the translation of the James River results to Fargo is uncertain. Also, the James River basin is more of a prairie pothole region than the upstream Red River basin. Climate change is currently not being considered in the Fargo-Moorhead risk reduction study.

What I'm going to talk about is Fargo -- the flood control study we've got going on for Fargo, North Dakota, Moorehead, Minnesota, on the Red River. As Bob Hirsch pointed out this morning, that was one of the biggest circle groups in the country where we had a trend for changes in discharge.

In the far north, 2009 was a flood of record. Some of you may have seen it on the news. It was a snowmelt flood. We had some time to prepare. We did a flood fight there that was successful, but this was some of the things -- some of the pictures from a flood fight. If anyone is interested, the picture on the right, those are called HESCOs. That comes with a mesh filled with sand and goes down like this with a layer of clay on the outside.

Sometimes you hear, well, why do we have to have a permanent project when flood fights are successful? It's a difficult job. Difficult job. Hard work. You know, Fargo in March is not the nicest place in the world to be fighting a flood.

And in this floodplain, you put in with communities of over 52 miles of protection put in. What do we have, 10 miles of sandbag levies, 34 miles of clay levies, put in by various entities. Eight miles of those HESCO bastions. And .3 miles of portadams, a little thing we were trying.

So like I said, it's a big effort. It's risky for the City of Fargo. Moorehead's part was on the Minnesota side. There are a lot smaller and a lot less people with floodplains. Fargo did not evacuate. These people were all behind these levies. Not only were there 52 miles put in, but they were raised as the flood crest predictions got raised.

Fargo, as we said, this was a flood of record. I think this will give a shot of some of the historic floods. You can't tell on this -- I have other slides that showed better, the upper trends. There are a couple of things to notice. There are a couple floods from the 1800s that are quite large, and we had a dry period, and getting wet again. 1997 was the last flood of record and that was the flood you'll see once a century until 2009.

Something about the Red River to the north, it's very flat. One of the things that's interesting is it flows north, and for a snowmelt flood basin, that causes a lot of problems, because as the snowmelt progresses to the north and the flood peak occurs in the north, you're running into more snow that hasn't melted and then running to ice. That complicates things. And it is very flat. It's an old glacial lake.

I think it's kind of interesting to see a couple of the hydrographs. The red box one is 2009, and you can see, it was rising really fast, and then it got cold. North Dakota gets cold, below zero. Things froze. The water was freezing, the roads froze, the layers of ice on the roads, all the runoff roads. We had to stop. You know, you can see where it went down for a while and then warmed up and started to run off again.

Another red line, fainter, is 1997, and sort of the same thing happened there. It was rising very fast, it got extremely cold, below zero -- they actually named blizzards in North Dakota. In '97, that was the year of the blizzards there that came in.

Then it became flattened out and then and came up again. Both times, without that cold weather, the flood peaks would have been even higher.

So this is where we started when we were looking at the project, looking at our study. We knew there was a trend in flood peaks. Here's a plot we had from 1901, which is the start of the continuous record. We had had this peak, this rise, in flood peaks. It was obvious it was the linear one.

The fifth year retrospect, moving average, looking back. You can see it in 1950, that fifth year peak looking back, was impressive at 4,000 cfs, and now it's 8,000, so it's over doubled. And when we designed the project, we didn't think we could ignore this. And as we heard very well this morning, there's no standardized way to evaluate that.

And so what we went with was an expert opinion elicitation, it's a formal process of getting the experts in to help give us guidance on what we should do to address this problem. And this plot is kind of an interesting one. It gets out some of the things other people have discussed. This is the annual precipitations of Fargo, and you can see some trends here but nothing -- the line of the seven-year average. Nothing that indicates you have that kind of trend you had in peak discharge. It just shows there's more of the precipitation going on. It shows those snowmelt events. One, you get the precip, and when it melts, as you can tell, it's probably as important as the annual total.

So we had our expert opinion panel. That was last September, and at least three of them are in the room here. David Ford, we hired to be the facilitator. Let's see. We had Mike Deering from the Corps who was present, Scott Dummer, Bob Hirsch, Rolf Olsen, David Raff, and Skip Vecchia. We tried to have a mix of people who were pretty familiar with the records in the north and national experts. We had official observers. The panels gets to give us their input in writing. The official observers get to talk, but they don't give us the official -- their thoughts that way.

This is a feasibility study. It's shared 50/50 with the locals, Fargo and Moorehead, and the states, and they had -- that were nominated by the City of Fargo, and Richard Pemble down there is from the City of Moorehead, recommended him.

I'll go right to some of the results from that panel, the EOE panel. Like I showed that graph when that trend was going up, that's what we worried about. That's what we were thinking about. Well, it didn't take along for the panel to go from that and zoom in on stationarity. That's not what they were thinking when we started, but that's where we ended up. And we said right from the summary, that's where we ended up, looking at concentrating on, that was nonstationarity.

In going right into the results on the panel. This is Number 3 from the executive summary. Number 1 and 2 didn't have to do with climate or stationarity. Here's the recommendations. And the way the process works, it isn't -- the panel doesn't say, well, here is the way to do it. They gave their opinions and discussed the opinions. So we kind of zoomed in on a methodology, not the details, but kind of the wave to attack the problem.

And so one of the recommendations was to break the period into two. We had a dry period from 1901 to 1941 and in 1942 to 2009 -- one of the panel members thought the break should be at '51. Another way that we could do it was to use a statistical test, and we did use a statistical test, the Pettit test. This is the results of it, and this will mean a lot more to most of you than it does to me, probably, but there's a very high, extremely high, level of confidence that there's a break in the record.

And I think Bob has said before that the Red River is sort of an outlier in the whole country in how extreme this break is. So this test was done on the climate change, stationarity, is one complication, but there's another one in the hydrologic study. There's two reservoirs upstream of Fargo/Moorehead and this test was done on the natural flows after we took out the reservoir impacts.

The fourth one felt a break in the two with the other one. Now, I said, so what do we do for the two parts? Use Log-Pearson III for each of the components, and then we got in some recommendations in the skew, which -- which you know, skew, to me, is one of those in Pandora's box. What do you do with that?

But so we did break it into two Log-Pearson III analyses, one from 1902 to 1941. The other one, the wet period, we went from 1941 to 2009. We included the 1800 floods. Then the skew for the wet period is minus 0.341, and for the dry is minus 0.159. Right now, we're using those as is. We did not adjust them.

So now we've got the two periods, remember. We've got the Log-Pearson III analysis form. What do we do to combine them? We've got the two. We know one is probably a good representation of 1940 to 1941 -- or 1900 to 1941, the other one for the wet period; but for the project design, we're worried about the future, so what do we do with those curves?

And there were a couple different trains of thought from the experts. One is, wait a minute, we're in a wet period now, assuming that we're moving to a dry period over time. They did emphasize that the record shows we'll be moving to a dry period someday. The size of this record from 1900 with some 1800 stuff to 2009. There are tree ring studies and other things going back several hundred years to show this wet-dry cycle in the Red River in the north has happened for hundreds of years.

The one way was, since it's wet, have to wait to go dry. Let us assume some probability for the whole -- some different probability for the wet and the dry over the whole 50-year study cycle. We went with weight -- assume from year zero that wet cycle, the wet frequency curve, for year 50 looked over this hundreds of years. About 65 percent of the time, it's been wet. 35 percent, it's been dry. And so for 50 years out, we used the 65/35. And for 25 years out, we just used something in between, 80 percent chance of wet, 20 percent chance of dry.

One of the other recommendations they had was using greater uncertainty. Since -- we've got a process now and it's different, but there's uncertainty before, and there's probably even more now, and so they recommended considering using a smaller portion period of record.

The number of years -- in our FDA analysis, when you go look at the flood damage analysis, you have to put in your period of frequency, years of record, and I don't think -- the longer years of record you put in, it affects the curves, and you run a Monte Carlo simulation. If we put in a shorter period, we will have more uncertainty. Right?

I don't say we finished this analysis. We got the numbers, the hydrologic analysis. We have not done the economic analysis yet. And so right now, what we're using, the wet -- we stated it as a period of record that was actually, in the calculations, for the wet period, 78 -- we used historic flux in the 80/20, and the dry was 39, and then had a weighting from the period of record, from this 80/20, which is 25 years out, used 70 years as a record, and 65/35, used 64 years of record.

So doing all that, where did we end up? And we're very accurate. We're right to the 1 cfs. Like I said, we finished this Monday, and we had all kinds of numbers floating around, and tried to keep it straight, and we went to the 1 cfs, so we knew where these numbers came from to try to keep things straight.

I guess I'll concentrate on the wet period. The wet period, 500 years, 67,000; the whole period, 80,000 cfs. That concerned us at first. Now, when we use the whole -- we did our initial analysis for the whole period of record. Now we're using a wet period, and the 500-year flood discharge has gone down. That looks counterintuitive. No, it makes sense. It fits the data.

And another thing, the better way to look at it is, when we went to this wet period over the dry, we increased the mean quite a bit in the log distribution. The mean went up quite a bit. Standard deviation went down a lot because we have a more -- less experience in the record, so a 500-year flood that depends more on the standard deviation than it does on the mean. Since our standard deviation went down, it makes sense to go down statistically.

That's still a concern for me. The locals would like this project be set to a 500-year flood. And I'm a little concerned to say, well, now, City, you can design -- you can lower your levies, because we're going to use this wet period. I think, in the back of my mind, there's some greater uncertainty to present that as an alternative. And I guess we could step back and use the shorter period or something like that to show the uncertainty. But with these numbers, I do have that concern.

The last ones were the natural flows. These are the ones we're actually using and including the reservoir effects. It's the same thing. It's just the numbers we're actually using. Here, instead of -- and probably, the project is going to be a diversion, not a levy, but we'd be designing, if we go from 500 year, 50,000 cfs to 58,000.

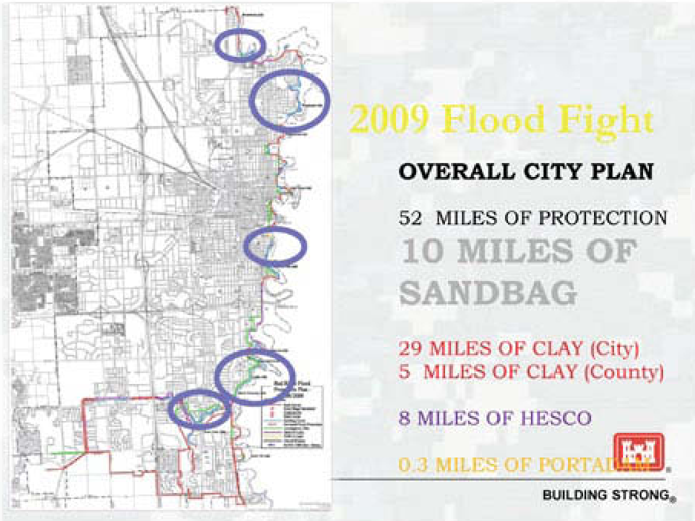
The last couple of things I have are the actual curves. The wet, blue; dry, red; the 80/20 and the 65/35; the other two curves in between, 60 -- what to think about, the 65/35, 80/20, is horizontally, not vertically. It's 80 percent of the way horizontal, rather than, than 80 percent vertically, if that makes sense to you. If you look at that vertically, it's on the 80/20, but looking horizontally, it does. And this is the same curve, just regulated.

That's really all I had on this. I had some other things -- one of the concerns I had in my 500-year flood going out, was just looking at nonstationarity, not looking at climate change, and I had a couple other ones that Dave Raff will be presenting later. He's with Jamestown with the climate. The curve would be going up, and -- the climate curve is going up. That's the concern I have. If we go with this wet period, dry period, broken record, you're lowering your curve really more than we should be at the upper end.

NOTE: *This is a transcript of the author's remarks at the workshop that has not been reviewed or edited by the author.*

Biography

Pat Foley received his Bachelor of Civil Engineering from the University of Minnesota in 1971 and his Master of Science (Civil Engineering) from Colorado State University in 1978. He has worked for the St. Paul District of the Corps of Engineers since 1972. Since 1987 he has been the Chief of the Hydraulics Section. He is currently working on hydraulic loading for Herbert Hoover Dike in Florida and on a re-assessment of the design flow line for the Atchafalaya Basin Floodway in Louisiana. He is also on a national team that is developing the Corps methodology for levee issue evaluation studies.


2009 Flood Fight
OVERALL CITY PLAN
52 MILES OF PROTECTION
10 MILES OF SANDBAG
29 MILES OF CLAY (City)
5 MILES OF CLAY (County)
8 MILES OF HESCO
0.3 MILES OF PORTADAM
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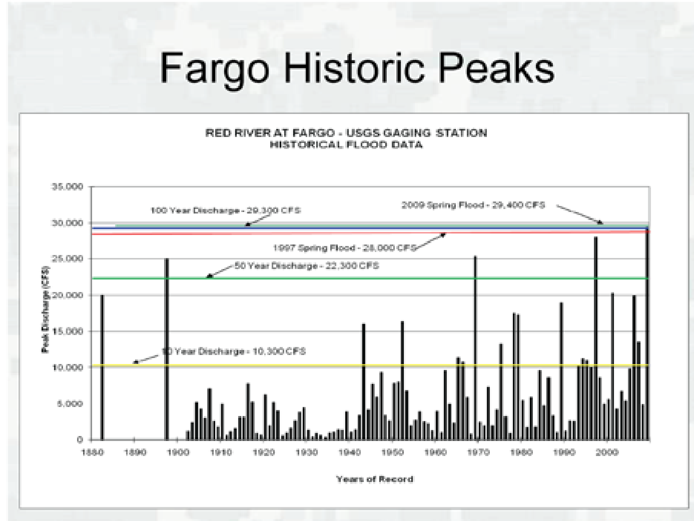
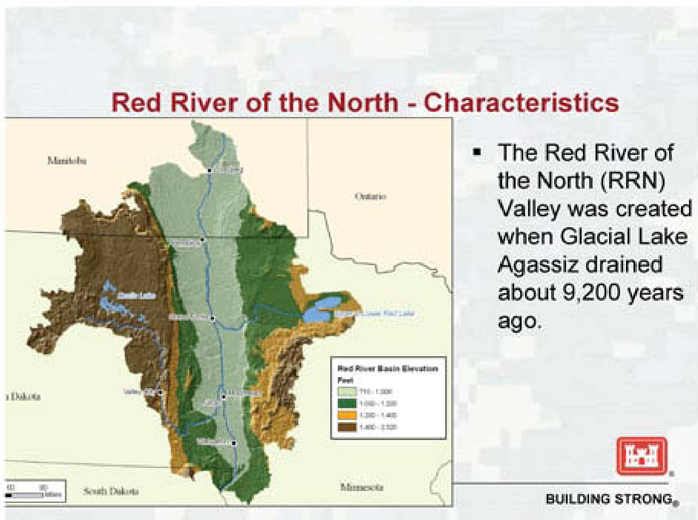

Fargo Historic Peaks
RED RIVER AT FARGO - USGS GAGING STATION
HISTORICAL FLOOD DATA
100 Year Discharge - 29,300 CFS
2009 Spring Flood - 29,400 CFS
1997 Spring Flood - 28,000 CFS
50 Year Discharge - 22,300 CFS
10 Year Discharge - 10,300 CFS
Peak Discharge (CFS)
Years of Record


Red River of the North - Characteristics
Manitoba
Ontario
South Dakota
Minnesota
Red River Basin Elevation
Feet
The Red River of the North (RRN) Valley was created when Glacial Lake Agassiz drained about 9,200 years ago.
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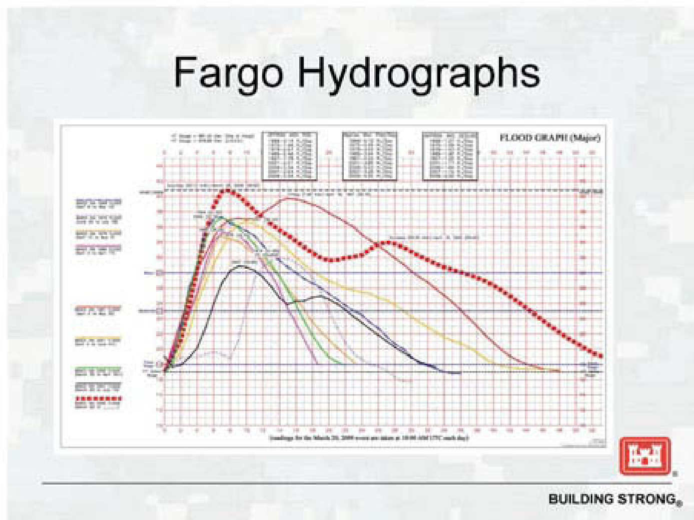
Fargo Hydrographs
FLOOD GRAPH (Major)
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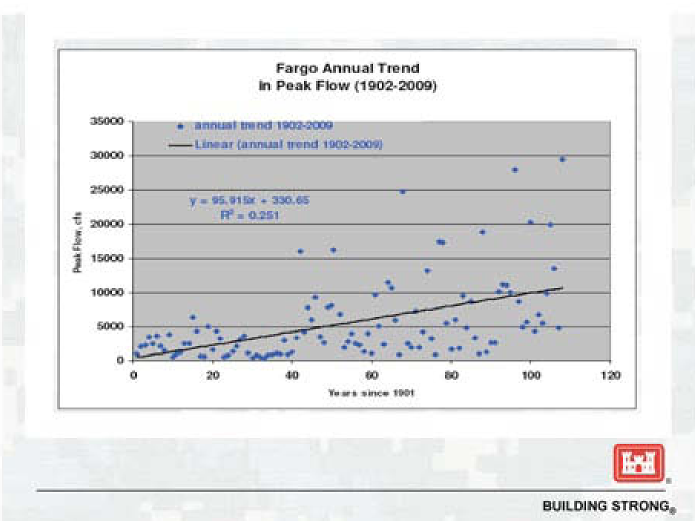
Fargo Annual Trend
in Peak Flow (1902-2009)
annual trend 1902-2009
Linear (annual trend 1902-2009)
y = 95.915x + 330.65
R² = 0.251
Peak Flow, cfs
Years since 1901
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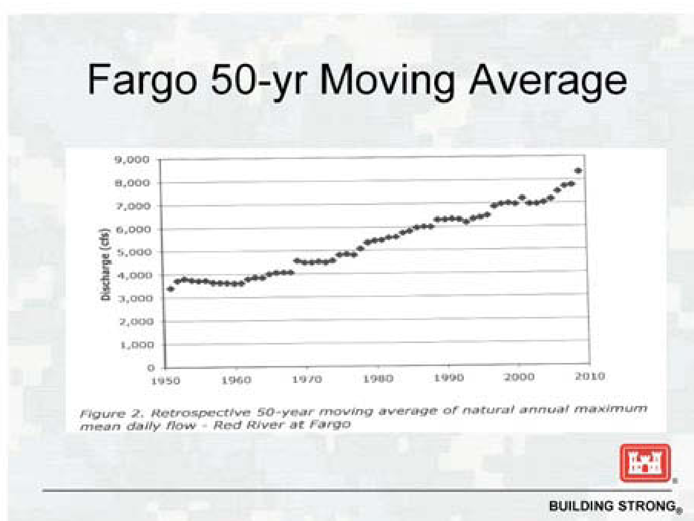
Fargo 50-yr Moving Average
Discharge (cfs)
Figure 2. Retrospective 50-year moving average of natural annual maximum mean daily flow - Red River at Fargo
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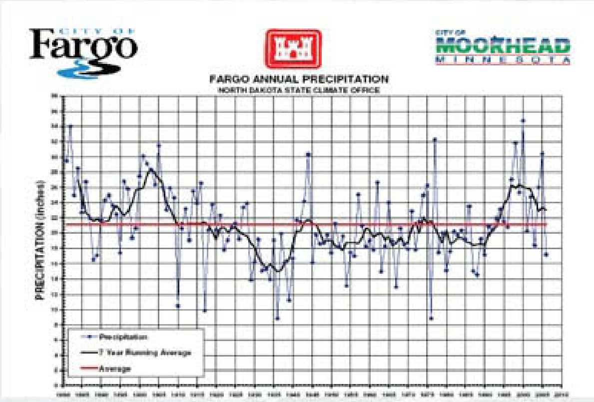

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EOE Results

- "experts rather quickly moved away from a discussion of climate change, per se, and focused instead on the apparent lack of stationarity in the flood flow frequency and magnitude data over the period of record (the last 110 years or so). "

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EOE Results

- 3. Using qualitative judgment, e.g., define the dry period as 1901-1941 and the wet period as 1942-2009; or define the dry period as 1901-1960 and the wet period as 1961-2009.
- Use statistical tests for homogeneity to determine where to divide the POR. The expert panel did not agree on the statistical tests, but did note work by Villarini, et al
- (USED PETTITT TEST)

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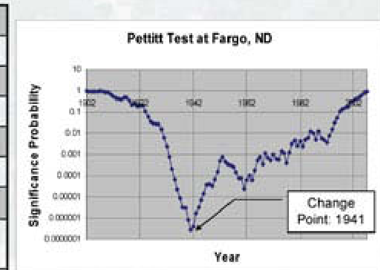
Pettitt Test

Statistics of Change	
N	108
K_{T+}	0
K_{T-}	1790
K_T	1790
Year $_{\text{Change Point}}$	1941
Standardized K	2.750
p_{oa} *(significance Probability associated with K_{T-})*	2.710E-7
p_{oa} *(significance probability associated with K_T)*	5.420E-7



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EOE Results

- 4. Fit a log Pearson III distribution separately to the dry components of the split record and the wet component, following generally the guidance in *Bulletin 17B*.
- Some members of the panel suggested using the total record to estimate the skew coefficient to be used for both components. Others suggested determining the skew coefficients for each portion of the POR separately. If the skew coefficients are close, an appropriately rounded average of the two could be used.
- (SKEW WET = -0.342, DRY = -0.159)

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EOE Results

- 5. Combine the "wet" and "dry" curves, and weight the probabilities for continued wet conditions versus a reemergence of dry conditions. Two schemes emerged from the majority of the experts' responses:
- Transition from wet to dry over time. For example, begin with p(wet)=1 and p(dry)=0 in year 1 of the project, moving to p(wet)=0.5 and p(dry)=0.5 in year 50, or move p(wet) from 1 to 0 over the life of the project.
- Do not change the probabilities over time. One proposed set of values was p(wet)=0.8 and p(dry)=0.2 over the entire 50-year project life. It was recognized that there is a good deal of subjectivity in the selection of these values, but experts felt it would be prudent to set a substantially higher probability on the wet condition than the dry one. Under this recommendation, setting p(dry) to zero was felt to be inappropriate, as a return to the dry condition is certainly possible.
- (USED 0.8 WET/0.2 DRY 25 YRS AND 0.65/0.35 FOR 50 YRS)

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EOE Results

- 6. Account for greater uncertainty. One suggestion was to use an equivalent POR in the Corps Hydrologic Engineering Center's Flood Damage Analysis (HEC-FDA) equal to the number of years of the smaller portion of the POR (either the wet portion or the dry portion).
- (Wet 78 years, dry 39 yrs, 80/20 70 years, 65/35 64 yrs)

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Flow-Frequency Analysis
Log-Pearson Type III

	Flows at a Given Exceedance Probability		
	10-yr	100-yr	500-yr
Wet Period	20, 811	46, 040	67, 163
Dry Period	5, 431	12, 106	18, 145
Combine: 0.8 Wet, 0.2 Dry	18, 668	43, 303	64, 026
Combine: 0.65 Wet, 0.35 dry	16, 788	40, 836	61, 183
Whole Period	16, 426	47, 115	80, 657

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Flow-Frequency Analysis
Regulated Flows

	Flows at a Given Exceedance Probability		
	10-yr	100-yr	500-yr
Wet Period	17,000	34,000	58,000
Dry Period	4,600	9,500	13,600
Combine: 0.8 Wet, 0.2 Dry	15,335	32,359	54,264
Combine: 0.65 Wet, 0.35 dry	13,859	30,852	50,939

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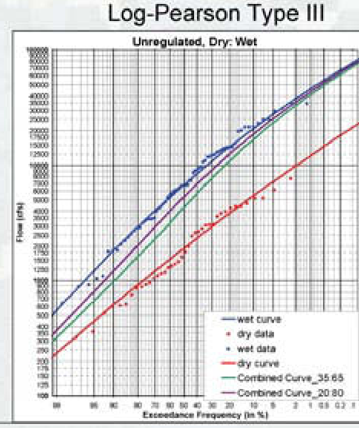
Flow-Frequency Analysis
Log-Pearson Type III



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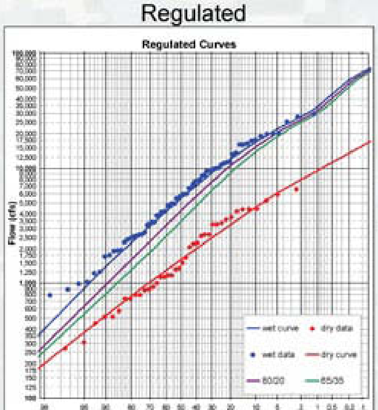
Flow-Frequency Analysis
Regulated



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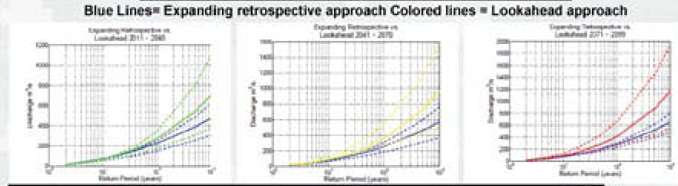
Climate Projections & Frequency Analysis

Source: *Raff, D.A, T. Pruitt, and L.D. Brekke, "A Framework for Assessing Flood Frequency Based on Climate Projection Information," Hydrol. Earth Syst. Sci., 13, 2119-2136, 2009.*

Flow-Frequency Curves for the James River at Jamestown

Blue Lines= Expanding retrospective approach Colored lines = Lookahead approach



100-yr Discharge Values in m³/s			
	2011- 2040	2041-2070	2071-2099
Expanding Retrospective	225	255	278
Lookahead	272	355	411
Percent Difference	17%	28%	32%

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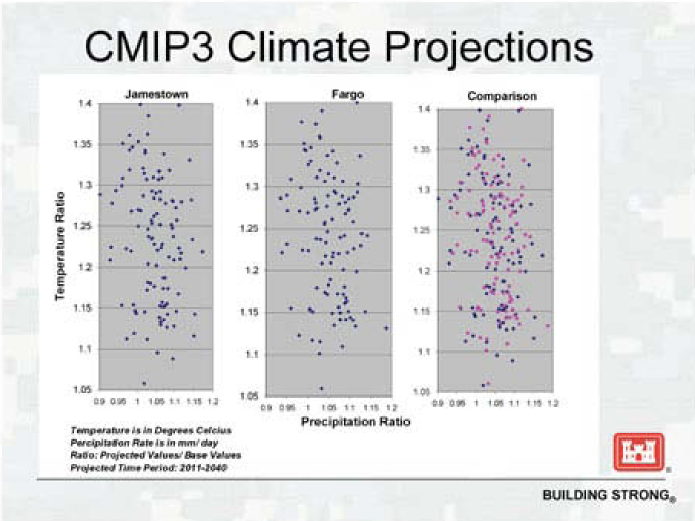
CMIP3 Climate Projections
Jamestown
Fargo
Comparison
Temperature Ratio
Precipitation Ratio
Temperature is in Degrees Celcius
Percipitation Rate is in mm/ day
Ratio: Projected Values/ Base Values
Projected Time Period: 2011-2040
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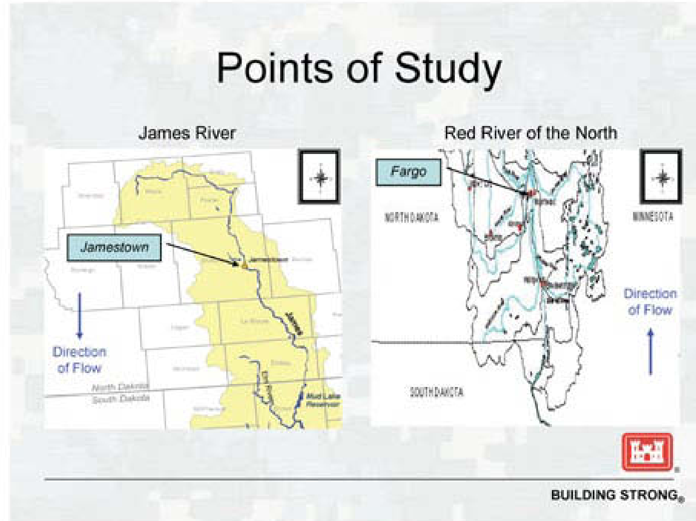
Points of Study
James River
Red River of the North
Jamestown
Direction of Flow
Fargo
NORTH DAKOTA
MINNESOTA
SOUTH DAKOTA
Direction of Flow
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Statistical Methods and Data Analysis

Stationarity: Wanted Dead or Alive

Harry Lins and Tim Cohn, U.S. Geological Survey

Abstract

Aligning engineering practices with natural process behavior would appear, on its face, to be a prudent and reasonable course of action. However, given what we know about the long-term characteristics of hydroclimatic processes, does the prudent and reasonable course necessarily portend improved water management practices? We argue herein that it does not, based on three aspects of observed hydroclimatic variability and statistical inference: Hurst-Kolmogorov phenonmenon; long-term persistence and the complications it introduces with respect to statistical understanding; and the arbitrariness of sampling choices with respect to trend testing. Sometimes it is better to employ a simple model with well-understood flaws than a sophisticated model whose correspondence to reality is uncertain.

Introduction

The periodic rediscovery of nonstationarity in hydrological processes invariably leads to an entertaining, and largely academic, debate. The theorist, calling for abandonment of stationarity altogether, offers a hopeless journey to despair, while the practitioner has to face the uncomfortable truth that we live in a changing world whose past is not a perfectly reliable guide to its future. It is a difficult conversation; *terra firma* is nowhere to be found. The real-world situation, where practical decisions are made, is typically less quixotic.

When nonstationarities arise due to well-understood deterministic processes, as with land-use change, for example, we can adjust for them using deterministic models. Nonstationarity of this sort presents a potential nuisance, but not a conceptual challenge. In fact, a traditional mission of federal water agencies has been to create nonstationarities through the construction of dams and levees.

The real challenge arises with respect to hypothesized non-stationarities that are fundamentally uncertain or chaotic. Accordingly, with respect to climate, it has been hypothesized that the addition of carbon dioxide to the atmosphere will alter the hydrological cycle. Details of future change – magnitude, sign, timing, and location – are unknown, and possibly unknowable, even for large watersheds. What should one do, if anything, with such "information"?

H_0 Process	Test	β^a	p-Value
White Noise	$T_\beta\{0,0,0\}$	0.0045	1.8e-27
MA(1)	$T_\beta\{0,0,\theta\}$	0.0046	1.9e-21
AR(1)	$T_\beta\{\Phi,0,0\}$	0.0047	5.2e-11
LTP	$T_\beta\{0,d,0\}$	0.0050	4.8e-3
ARMA(1,1)	$T_\beta\{\Phi,0,\theta\}$	0.0053	1.7e-4
LTP + AR(1)	$T_\beta\{\Phi,d,0\}$	0.0045	7.1e-2

a Trend magnitude, $\hat{\beta}$, is expressed in units of °C/year.

Table 1. Estimates of trend magnitudes and p-values corresponding to various models fitted to the annual Northern Hemisphere temperature departure data, 1856–2004.

The purpose of this paper is to address three points associated with stationarity, nonstationarity, and trend testing in the context of climatic change and water resources management. First, with respect to fundamental physics like the Big Bang and planetary motions, it is obvious that nonstationarity exists. The time has come to dispense with this question.

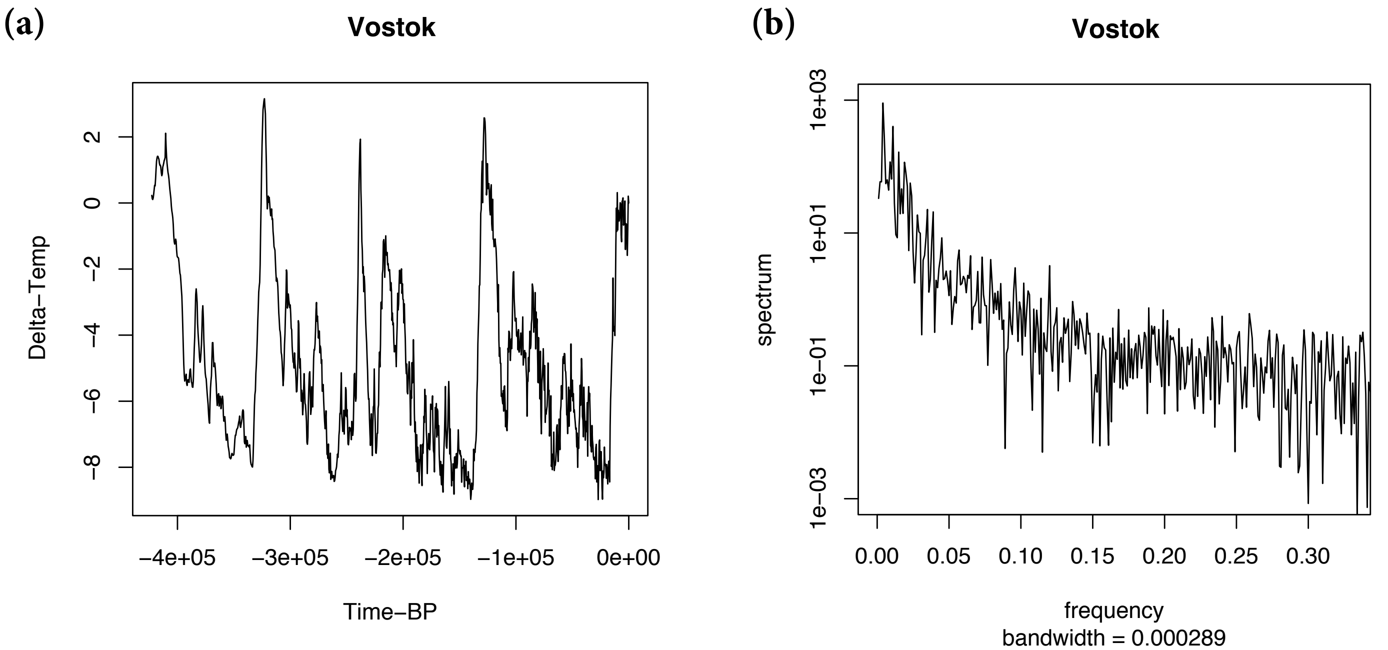

Figure 1. Time series plot of a 450,000-year segment of the reconstructed temperature record from the Vostok ice core in East Antarctica (a), and its corresponding power spectrum (b).

The second point, paradoxically opposing the first, is that given the complexity, scale, and long-term persistence (Cohn and Lins, 2005) of climatic systems, combined with a paucity of observational records, stationarity and non-stationary are essentially indistinguishable to the data analyst except in those cases where changes in the underlying processes are so dramatic that no statistical assessment is necessary. In short, rigorous statistical evidence of climatic nonstationarity, *per se*, is not going to be easily found and is unlikely to be convincing (Villarini et. al, 2009).

The third point is cautionary; testing for trends is exceedingly difficult for reasons both practical and conceptual. It is easy to fool oneself. Results turn out to be highly sensitive to arbitrary decisions about data and subjective decisions about how Mother Nature behaves in the absence of whatever effect is under consideration. Cohn and Lins (2005) state: "The concept of statistical significance is meaningless when discussing poorly understood systems." Koutsoyiannis goes further, questioning whether the concept of "trend" can be rigorously defined (personal communication, 2005).

Hurst-Kolomogorov Phenomenon

Hurst's 1951 observation that Nile streamflows, though apparently stationary, exhibit persistent excursions from their mean value was the first clear characterization of "long-term persistence" (LTP) in nature. Nearly a decade earlier, however, Kolmogorov had formulated the mathematical basis of the "Hurst phenomenon." Subsequently, Mandelbrot found LTP everywhere he looked, most noticeably in large scale natural processes, and coined the word "fractals" to describe the entire class of self-similar phenomena.

Hydrologists often refer to LTP as fractional Gaussian noise (fGn) or "long memory", which differentiates it from the "short-term persistence" (STP) associated with Autoregressive-Moving Average (ARMA) models (Loucks et al.,1981). Both STP and LTP processes are stationary; LTP is not a "random walk." The fundamental property of STP systems is that correlations die off exponentially between observations that are sufficiently "far apart" in time; for LTP systems, the decline is polynomial, which is much "slower" in the sense that dependencies among observations may exist over thousands or even millions of years. This has profound implications for system behavior.

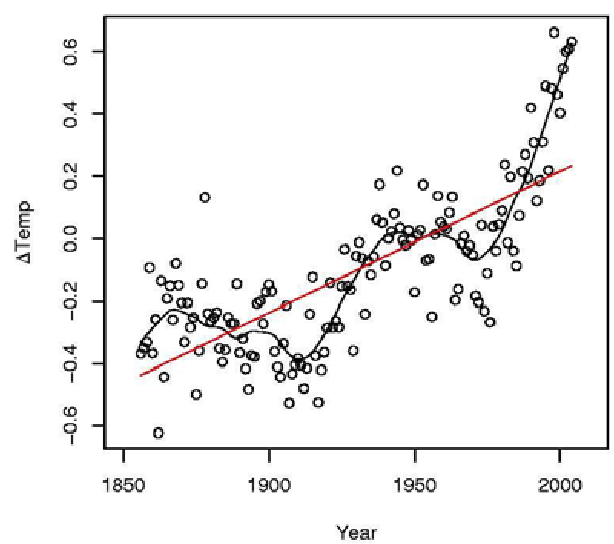

Figure 2. Annual departures from the period-of-record mean northern hemisphere temperature in degrees C, 1856–2004, with least squares fit (red line) and loess smooth (black line). From Cohn and Lins, 2005.

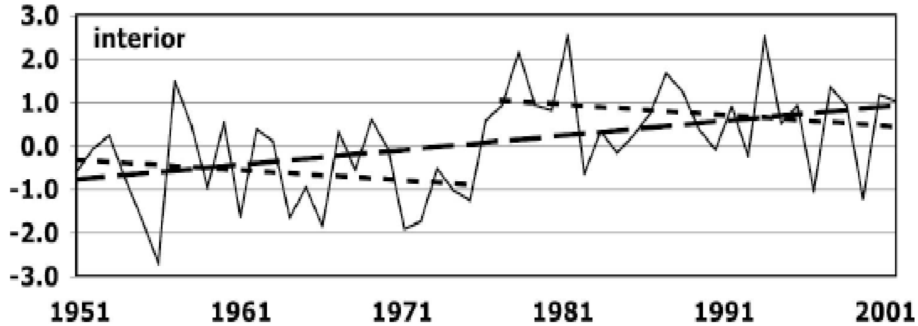

Figure 3. Annual departures from the period of record mean temperature in degrees C for Alaska's Interior climate region from 1951 to 2001. The least squares linear regression lines for 1951–2001, 1951–75, and 1977–2001 are included. From Hartmann and Wendler, 2005.

To see an example of LTP, consider a 450,000-year segment of the temperature record reconstructed from the Vostok ice core in East Antarctica (Figure 1a). The figure suggests a complex pattern around a fixed mean with possibly periodic excursions. When one considers the spectrum of the process (Figure 1b), one sees the downward slope characteristic of LTP. This is "red noise" and it is very different from the flat spectrum that characterizes independent and identically distributed (IID) white-noise or STP processes.

Though stationary, LTP processes exhibit long excursions, just like finite realizations from nonstationary processes. As Mandelbrot and Wallis (1969, pp. 230–231) observed, "[a] perceptually striking characteristic of fractional noises is that their sample functions exhibit an astonishing wealth of 'features' of every kind, including trends and cyclic swings of various frequencies." It is easy to imagine that LTP could be mistaken for trend or nonstationarity. However, assuming that LTP is present in climatic processes begs the question: Does it matter?

LTP and Misspecification of the Null Hypothesis

Most hydroclimatic trend analyses report two distinct measures, trend magnitude and the corresponding statistical significance. As noted by Cohn and Lins (2005), trend magnitude can be reported with little ambiguity, as this measure appears to be insensitive to the type of estimator employed. In general, distinct estimators, encompassing a variety of underlying assumptions about the data, produce similar estimates of change for a given variable. In contrast, statistical significance is highly influenced by the choice of test because significance is critically dependent upon the null hypothesis that, in turn, reflects subjective expectations.

An example of the insensitivity of trend magnitude and sensitivity of statistical significance to test type is evident in the record of annual mean Northern Hemisphere temperature for the period 1856-2004 (Figure 2). The plot, depicting temperature departures from the period-of-record mean, exhibits a very clear overall increasing trend, although the pattern contains considerable structure with multi-decadal periods of both increasing and decreasing trends. The results of six distinct trend tests applied to this dataset appear in Table 1. Note the similarity in the calculated trend magnitude among the estimators, with values ranging between 0.45 and 0.53 °C per century.

Now consider the p-values associated with each test, where the null hypothesis is that there has been no change over time. The simplest test, OLS regression, assumes that the temperature observations are IID. Under this assumption, the p-value is a very highly significant $1.8*10^{-27}$. An autoregressive (AR1) model, which allows for short-term persistence, yields a p-value of $5.2*10^{-11}$, 16 orders of magnitude larger and still highly significant. The p-value for the LTP+AR(1) test, which considers both short- and long-term persistence, is about 7%, which is not significant under the null hypothesis. By changing from a test that assumes no change over time, to one that accounts for trend-like properties, 25 orders of magnitude of significance vanished. These results demonstrate the critical importance of selecting a test for which the underlying assumptions are consistent with the characteristics of the process.

Koutsoyiannis and Montanari (2007), considering the same question from a slightly different perspective, show that a time series consisting of 1700 observations from an LTP stochastic process actually contains the information equivalent of only 3 independent observations. It is hard to overstate the importance of this observation. Under the circumstances, it would be very difficult to claim that a process was nonstationary as opposed to simply behaving in accordance with its LTP character.

Arbitrariness of Sampling Choices

Another troublesome characteristic of trend testing is the sensitivity to small perturbations in a time series. Most hydroclimatic variables have record lengths less than 100 years and, given the multi-decadal to century scale variations commonly observed in such records, one can typically find multiyear periods of both uptrends and downtrends at any given station. In such instances, the decisions made by the analyst with respect to trend test beginning and ending dates can have dramatic effects on the final result, not just influencing trend magnitude, but trend direction as well.

Hartmann and Wendler (2005) present a clear example of this with respect to regional temperature change in Alaska. They found that, although surface air temperature had increased in Alaska between 1951 and 2001, it had not done so monotonically (Figure 3). Temperatures in all climatic divisions of Alaska, except the Arctic, had undergone two sequent multidecadal periods of small decreasing trends separated by a +3°C step change that occurred in 1976-1977. The step

Figure 4. Summary of trends in annual instantaneous peak streamflow for the 60-year period 1948-2007 at 1491 stations from the USGS Hydro-Climatic Data Network (NCDN): a) trend direction and significance, with increasing trends in blue and decreasing trends in red, and those significant at the 0.05 level signified by open triangles (based on the Adjusted Likelihood Ratio Test [ALRT]); b) frequency distribution of trends by magnitude; c) frequency distribution of p-values associated with stations having increasing peak streamflow; and d) frequency distribution of p-values associated with stations having decreasing peak streamflow.

change, which they suggested was likely associated with a shift in the Pacific Decadal Oscillation, was so dramatic that any trend analysis that began before 1976 and ended after 1977 would show a warming, whereas any analysis that ended before 1976 or that began after 1977 would show a cooling. They conclude that "the use of trend line analysis in climate change research depends greatly upon the time period studied, and results can be biased when an abrupt climate change is observed during the study period. It has been demonstrated that the sudden changes of 1976 observed in Alaska have a profound effect on temperature trends. Shifts and multiyear anomalies result in temperature trends over periods that can differ substantially (even in sign) from the trend of the full period."

Stationarity, Dead or Alive

A fundamental component of engineering design and practice involves predicting or characterizing future conditions with sufficient precision that the consequences of design choices can be evaluated. For example, spillways are designed with the intent of safely passing the largest flood that will occur during the future life of the project. We need to estimate that flood.

The traditional approach for characterizing future events is to assume that the future will resemble the past and that the past can be represented by a sample of observations drawn from the same physical process from which the future will be generated. While the future will not repeat the past, its properties can be inferred from the past. In some cases this assumption is not valid. For example, urbanization may double the magnitude of 100-year-flood peaks, a phenomenon that has been observed throughout much of the United States (Konrad, 2003). Consideration of such well understood nonstationarities is important and clearly appropriate.

However, what about the hypothesized climate-related nonstationarities? This is not so easy, at least with respect to those associated with flood generation. We don't truly understand the processes, and existing data simply do not show a very substantial effect. An examination of flood records corresponding to undeveloped watersheds over the past 60 years (see Figures 4a, b) shows clusters of trends going in both directions, but no consistent trend overall. If one looks at the p-values associated with the trends (Figures 4c, d), one sees essentially no evidence of trends. Without physical understanding or statistical evidence, it is hard to see much sense in admitting nonstationarity into the analysis, although one might want to recognize the increased uncertainty that potential climate change introduces into the analysis.

Conclusions

This paper addresses several topics related to climatic nonstationarity. The first conclusion is that nonstationarity exists; it is a characteristic of the natural world. The second conclusion is that, as a general rule, it is very difficult to conduct tests on real data that will confirm the presence of LTP given the small amount of data and the inherent difficulties in trying to draw inferences about poorly understood systems. Finally, with respect to climate, it appears that the nonstationary hydro-climatic effects to date are too small to measure, suggesting that their magnitude is eclipsed by other sources of variability. Given all of the above, it seems reasonable to conclude that stationarity is too valuable to discard casually, particularly in response to an academic observation.

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Biography

Harry Lins is a hydrologist in the USGS Office of Surface Water. A climatologist by training, his work has focused on characterizing the surface water response to climate with an emphasis on regional streamflow variability, long-term trends, and the statistical techniques appropriate for such analyses. Most recently, he has investigated the effects of long-term persistence on trend and significance testing in hydroclimatic time series. He has authored more than 60 journal articles and book chapters. Harry coordinated the USGS Global Change Hydrology Program from 1989 to 1997, was co-chair of the hydrology and water resources working group for the IPCC First Assessment Report, and is a co-developer of the USGS WaterWatch web site. He holds a Ph.D. from the University of Virginia.

Biography

Tim Cohn, currently a hydrologist in the USGS Office of Surface Water, has co-authored more than 35 papers on methods for estimating flood risk and other topics. He previously served as USGS Science Advisor for Hazards, where he helped coordinate USGS programs that apply science to the challenge of reducing the Nation's vulnerability to natural hazards. As the American Geophysical Union's 1995-96 AAAS Congressional Science Fellow, he served as legislative assistant to Senator Bill Bradley on issues related to energy and the environment. Tim holds M.S. and Ph.D. degrees from Cornell University and a B.A. from Swarthmore College.

Hurst-Kolomogorov Processes and Uncertainty

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Abstract

The non-static, ever changing hydroclimatic processes are often described as nonstationary. However, revisiting the notions of stationarity and nonstationarity, which are defined within stochastics, it may be understood that claims of nonstationarity cannot stand unless the evolution in time of the statistical characteristics of the process is known in deterministic terms, in particular for the future. This however can hardly be the case, because deterministic predictions are difficult, especially of the future. Thus, change is not synonymous to nonstationarity, and even prominent change at a multitude of time scales, small and large, can be described satisfactorily by a stochastic approach admitting stationarity. This "novel" description does not depart from the 60- to 70-year old pioneering works of Hurst on natural processes and of Kolmogorov on turbulence. Contrasting stationary with nonstationary has important implications in engineering and management. The stationary description with Hurst-Kolmogorov stochastic dynamics demonstrates that nonstationary and classical stationary descriptions underestimate the uncertainty. This is illustrated using several examples of hydrometeorological time series, which also show the consistency of the Hurst-Kolmogorov approach with reality. A final example demonstrates how this framework was implemented in the planning and management of the water supply system of Athens, Greece, also in comparison with alternative nonstationary modelling approaches, including a trend-based and a climate-model-based approach.

«Αρχή σοφίας ονομάτων επίσκεψις» (Αντισθένης)
"The start of wisdom is the visit (study) of names" (Antisthenes; ~445-365 BC)

Introduction

Perhaps the most significant contribution of the intensifying climatic research is the accumulation of evidence that climate has never in the history of Earth been static. Rather, it has been ever changing at all time scales. This fact, however, has been hard, even for scientists, to accept, as displayed by the inflationary (and thus non scientific) term "climate change". The introduction of this term reflects a belief, or expectation, that climate would normally be static, and that its change is something extraordinary which to denote we need a special term ("climate change") and which to explain we need to invoke a special agent (e.g. anthropogenic influence). Examples indicating this problem abound, e.g., "*climate change is real*" (Tol, 2006) or "*there is no doubt that climate change is happening and that we should be taking action to address it now*" (Institute of Physics, 2010). More recently the scientific term "nonstationarity", contrasted to "stationarity", has also been recruited to express similar, or identical ideas to "climate change". Sometimes their use has been dramatized, perhaps to better communicate a non-scientific message, as in the recent popular title of a paper in Science: "*Stationarity is Dead*" (Milly *et al.*, 2008). We will try to show below, in section 2, that such use of these terms is in fact a diversion and misuse of the real scientific meaning of the terms.

Insisting on the proper use of the scientific terms "stationarity" and "nonstationarity" is not just a matter of semantics and of rigorous use of scientific terminology. Rather, it has important implications in engineering and management. As we demonstrate in section 2, nonstationary descriptions of natural processes use deterministic functions of time to predict their future evolution, thus explaining part of the variability and eventually reducing future uncertainty. This is consistent with reality only if the produced deterministic functions are indeed deterministic, i.e., exact and applicable in future times. As this is hardly the case as far as future applicability is concerned (according to a quotation attributed to Niels Bohr, "*prediction is difficult, especially of the future*"), the uncertainty reduction is a delusion and results in a misleading perception and under-estimation of risk.

In contrast, proper stationary descriptions, which, in addition to annual (or sub-annual) variability, also describe the over-annual climatic fluctuations, provide more faithful representations of natural processes and help us characterize the future uncertainty in probabilistic terms. Such representations are based on the Hurst-Kolmogorov (HK) stochastic dynamics (section 3), which has essential differences from typical random processes. The HK representations are essential for water resources planning and management, which apparently demand long time horizons and can have no other rational scientific basis than probability (or its complement, reliability).

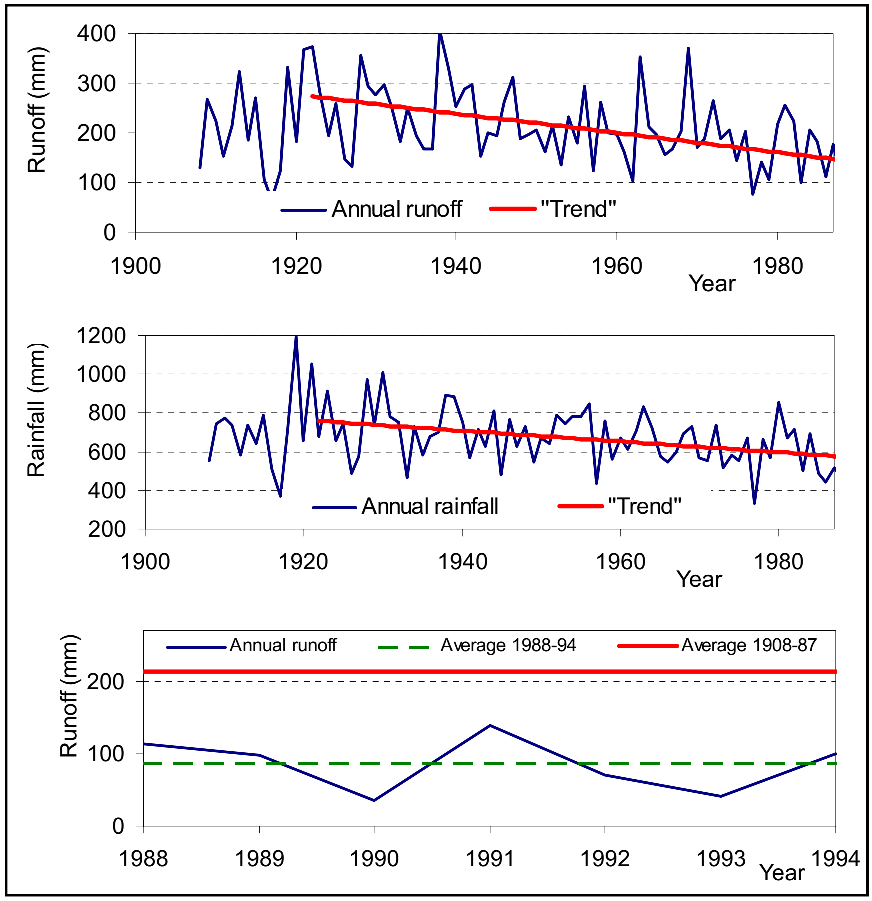

Figure 1. Time series of runoff (upper) and rainfall (middle) in the Boeoticos Kephisos River basin from the beginning of observations to 1987, with focus of the runoff during the severe, 7-year (1988-94) drought period (lower).

It is thus essential to illustrate the ideas discussed in this paper and the importance of rigorous use of scientific concepts through a real-world case study of water resources management. The case study we have chosen for this purpose is the complex water supply system of Athens. While Athens is a very small part of Greece (about 0.4% of the total area), it hosts about 40% of its population. The fact that Athens is a dry place (annual rainfall of about 400 mm) triggered the construction of water transfer works from the early stages of the long history of the city (Koutsoyiannis *et al.*, 2008b) . The modern water supply system transfers water from four rivers from up to about 200 km away from Athens.

Figure 1 (upper panel) shows the evolution of the runoff of one of these rivers, the Boeoticos Kephisos River (in units of equivalent depth over its about 2,000 km^2 catchment) from the beginning of observations to 1987. A substantial falling trend is clearly seen in the time series. The middle panel of Figure 1 shows the time series of rainfall in a raingauge in the basin, where a trend is evident and explains (to a large extent) the trend in runoff. Most interesting is the runoff in the following seven years, 1988-1994, shown in the last panel of Figure 1, which is consistently below average, thus manifesting a long-lasting and severe drought that shocked Athens during that period. The average during these seven years is only 44% of the average of the previous years. A typical interpretation of such time series would be to claim nonstationarity, perhaps attributing it to anthropogenic global warming, etc. However, we will present a different interpretation of the observed behaviour and its implications on water resources planning and management (section 4). For Athens, these implications were particularly important even after the end of the persistent drought, because it was then preparing for the Olympic games—and apparently these would not be possible in water shortage conditions. Apparently, good planning and management demand a strong theoretical background and proper use of fundamental (but perhaps forgotten or abused) notions.

Visiting Names, Stationarity and Nonstationarity

Finding invariant properties within motion and change is essential to science. Newton's laws are eminent examples. The first law asserts that, in the absence of an external force, the position x of a body may change in time t but the velocity $u := \mathrm{d}x/\mathrm{d}t$ is constant. The second law is a generalization of the first for the case that a constant force F is present, whence the velocity changes but the acceleration $a = \mathrm{d}u/\mathrm{d}t$ is constant and equal to F/m, where m is the mass of the body. In turn, Newton's law of gravitation is a further generalization, in which the attractive force F (weight) exerted, due to gravitation, by a mass M on a body of mass m at a distance r is no longer constant. In this case, the quantity $G = F\,r^2/(m\,M)$ is constant, whereas in the application of the law for planetary motion another constant emerges, i.e., the angular momentum per unit mass, $(d\theta/dt)\, r^2$, where θ denotes angle.

However, whilst those laws give elegant solutions (e.g., analytical descriptions of trajectories) for simple systems comprising two bodies and their interaction, they can hardly derive the irregular trajectories of complex systems. Complex natural systems consisting of very many elements are impossible to describe in full detail and their future evolution is impossible to predict in detail and with precision. Here, the great scientific achievement is the materialization of macroscopic descriptions that need not model the details. This is essentially done using probability theory (laws of large numbers, central limit theorem, principle of maximum entropy). Here lies the essence and usefulness of the stationarity concept, which seeks invariant properties in complex systems.

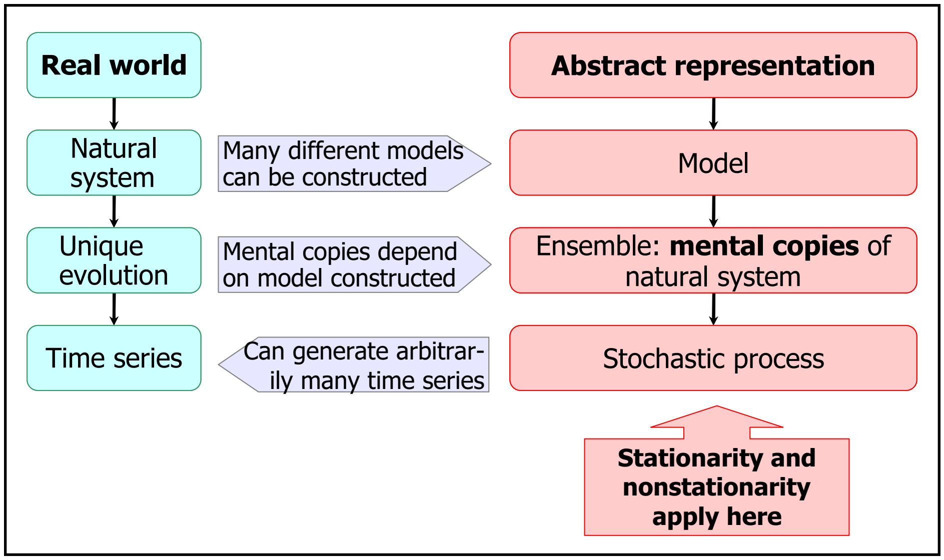

Figure 2 Schematic for the clarification of the notions of stationarity and nonstationarity.

According to the definitions quoted from Papoulis (1991), "*A stochastic process* $\underline{x}(t)$ *is called strict-sense stationary … if its statistical properties are invariant to a shift of the origin*" and "*… is called wide-sense stationary if its mean is constant* ($E[\underline{x}(t)] = \eta$) *and its autocorrelation depends only on [time difference]* τ*…*, ($E[\underline{x}(t+\tau)\,\underline{x}(t)] = R(\tau)$)". We can thus stress that the definition of stationarity applies to stochastic processes (rather than to time series; see also Koutsoyiannis, 2006b). Processes that are not stationary are called nonstationary and some of their statistical properties are *deterministic* functions of time. Figure 2 helps us to further clarify the definition. The left part of this graphic symbolizes the real world. Any natural system we study has a unique evolution (a unique trajectory in time), and if we observe this evolution, we obtain a time series. The right part of the graphic symbolizes the abstract world, the models. Of course, we can build many different models of the natural system, any one of which can give us an ensemble, i.e., mental copies of the real-world system. The idea of mental copies is due to Gibbs, known from statistical thermodynamics. An ensemble can also be viewed as multiple realization of a stochastic process, from which we can generate synthetic time series. Clearly, the notions of stationarity and non-stationarity apply here to the abstract objects—not to the real-world objects. In this respect, profound conclusions such as that hydroclimatic processes are nonstationary or that "stationarity is dead" may be pointless.

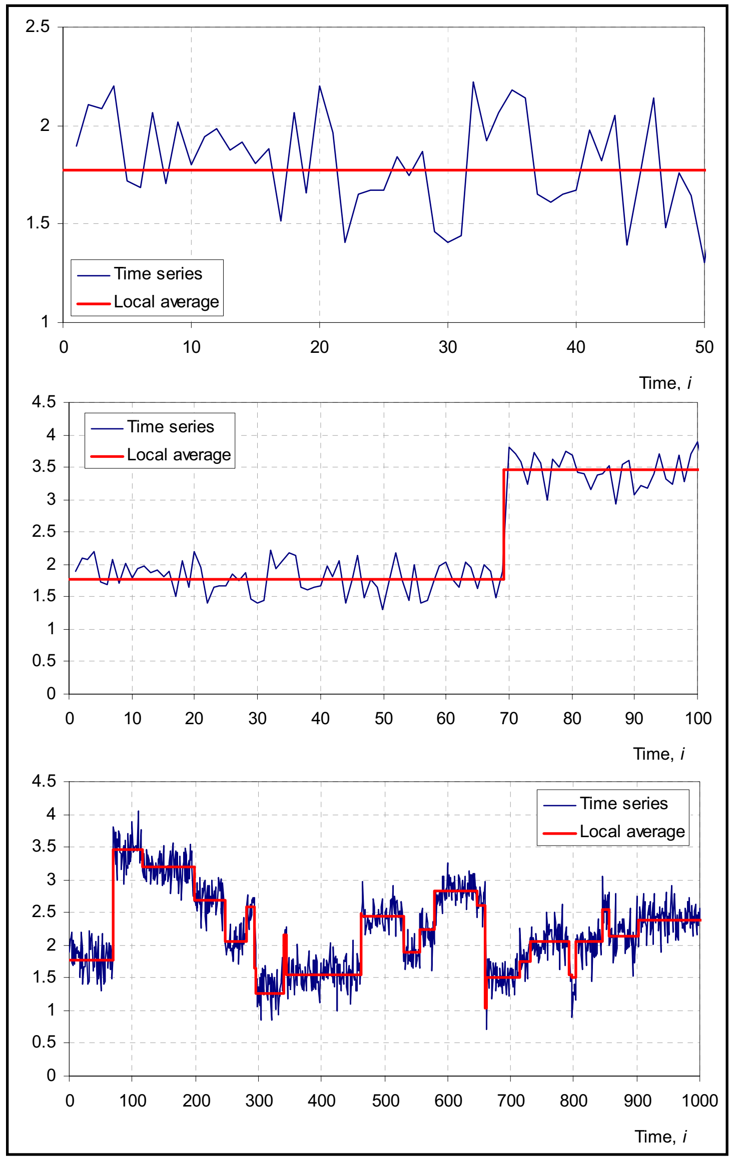

Figure 3. A synthetic time series for the clarification of the notions of stationarity and nonstationarity (see text); (upper) the first 50 terms; (middle) the first 100 terms; (lower) 1000 terms.

To further illustrate the notion of stationarity we use an example of a synthetic time series, shown in Figure 3, whose generating model will be unveiled below, along with some indication that it could be a plausible representation of a complex natural system. The upper panel of the figure depicts the first 50 terms of the time series. Looking at the details of this irregular trajectory, one could hardly identify any property that is constant. However, in a macroscopic—i.e., statistical—description one could assume that this time series comes from a stochastic process with a mean constant in time ($E[\underline{x}_i] = \mu$, where E denotes expected value, i denotes discrete time, x_i is the time series and $\underline{x}_i$ is the stochastic process). In a similar manner, one can assume that the process has a standard deviation σ constant in time (i.e., $E[(x_i - \mu)^2] = \sigma^2$) and so on. Both μ and σ are not material properties of the process (that for instance could be measured by a certain device), but abstract statistical properties.

The middle panel of Figure 3 depicts 100 terms of the time series. One could easily identify two periods, $i < 70$ with a local time average $m_1 = 1.8$ and $i \geq 70$ with a local time average $m_2 = 3.5$. One could then be tempted to use a nonstationary description, assuming a “change” or “shift” of the mean at time $i = 70$. But this is just a temptation (explained by the adherence to the classical views of natural phenomena as either “clockwork” or “dice throwing”; see Koutsoyiannis, 2009); it does not reflect any objective scientific truth and it is not the only option. Rather, a stationary description is still possible.

In fact, as is more evident from the lower panel of Figure 3, the stationary description corresponds to the actual model used to generate the time series. This model consists of the superposition of: (a) a stochastic process, with values m_j derived from the normal distribution $N(2, 0.5)$, each lasting a period τ_j exponentially distributed with $E[\underline{\tau}_j] = 50$ (the thick line with consecutive plateaus); and (b) white noise, with normal distribution $N(0, 0.2)$. Nothing in this model is nonstationary and, clearly, the process of our example is stationary.

In this example, distinguishing stationarity from nonstationarity is a matter of answering a simple question: Does the thick line of plateaus in Figure 3 represent a known (deterministic) function or an unknown (random) function? In the first case (deterministic function), we should adopt a nonstationary description, while in the second case (random function, which could be assumed to be a realization of a stationary stochastic process), we should use a stationary description. As stated above, contrasting stationary with nonstationary descriptions has important implications in engineering and management. To see this we have copied in Figure 4 the lower panel of Figure 3, now in comparison to a “mental copy”, which was constructed assuming nonstationarity. We also did the same in Figure 5, but assuming stationarity. In Figure 4 (the nonstationary description), because nonstationarity implies that the sequence of consecutive plateaus is a deterministic

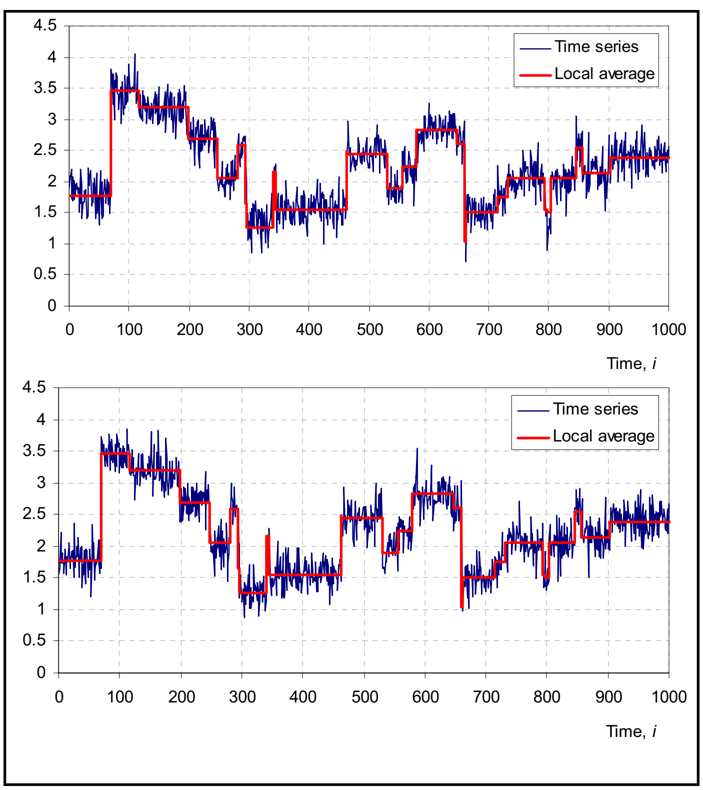

Figure 4. The time series of Figure 3 (upper) along with a mental copy of it (lower) assuming that the local average is a deterministic function and thus identical with that of the upper panel.

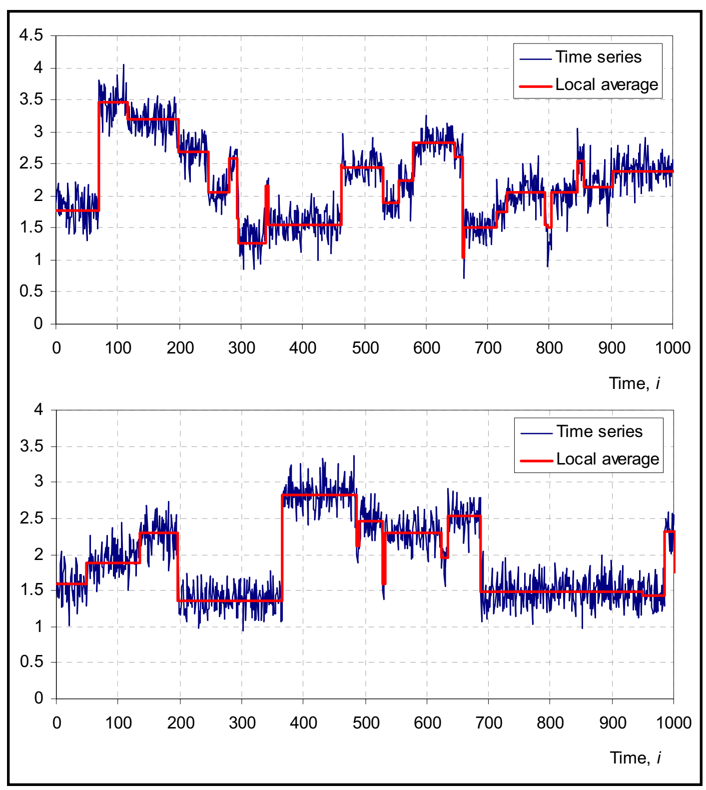

Figure 5. The time series of Figure 3 (upper) along with a mental copy of it (lower) assuming that the local average is a random function, i.e. a realization of the stochastic process described in text, different from that of the upper panel.

function of time, the thick lines of plateaus is exactly the same in the two copies. The uncertainty, expressed as the unexplained variance, i.e., the variance of differences between the thick line of plateaus and the rough line, is (by construction of the process) $0.2^2 = 0.04$. However, in Figure 5 (the stationary description) the two copies have different random realizations of the line of plateaus. As a result, the total variance (that of the "non-decomposed" time series) is unexplained, and this is calculated to be 0.38, i.e., almost 10 times greater than in the nonstationary description. Thus, a nonstationary description reduces uncertainty, because it explains part of the variability. This is consistent with reality only if the produced deterministic functions are indeed deterministic, i.e., exact and applicable in future times. As this is hardly the case, as far as future applicability is concerned, the uncertainty reduction is a delusion and results in a misleading perception and underestimation of risk.

In summary, the example illustrates that (a) stationary is not synonymous to static; (b) nonstationary is not synonymous to changing; (c) in a nonstationary process the change is described by a deterministic function; (d) nonstationarity reduces uncertainty (because it explains part of variability); and (e) unjustified/inappropriate claim of nonstationarity results in underestimation of variability, uncertainty and risk. In contrast, a claim of nonstationarity is justified and thus, indeed, reduces uncertainty, if the deterministic function of time is constructed by deduction (the Aristoteleian *apodeixis*), and not by induction (direct use of data). Thus, to claim nonstationarity, we must: (a) establish a causative relationship; (b) construct a quantitative model describing the change as a deterministic function of time; and (c) ensure applicability of the deterministic model in future time.

Because recently the inflationary use of the term "nonstationarity" in hydrology has been closely related to "climate change", it is useful to examine whether the terms justifying a nonstationary description of climate do hold true or not. The central question is: Do climate models (also known as general circulation models—GCMs) enable a nonstationary approach? More specific versions of these question are: Do GCMs provide credible deterministic predictions of the future climate evolution? Do GCMs provide good predictions for temperature and somewhat less good for precipitation (as often thought)? Do GCMs provide good predictions for global and continental scales and, after downscaling, for local scales? Do GCMs provide good predictions for the distant future (albeit less good for the nearer future, e.g., for the next 10-20 years—or for the next season or year)? To the author's opinion, the answers to all these questions should be categorically negative. Not only are GCMs unable to provide credible predictions for the future, but they also fail to reproduce the known past (see Koutsoyiannis *et al.*, 2008a; Anagnostopoulos *et al.*, 2009). An additional, very relevant question is: Is climate predictable in deterministic terms? Again the author's answer is negative (Koutsoyiannis, 2006a; 2009). Only stochastic climatic predictions could be scientifically meaningful. In principle, these could also include nonstationary descriptions wherever causative relationships of climate with its forcings are established. But until such a stochastic theory of climate, which includes nonstationary components, could be shaped, there is room for developing a stationary theory that characterizes future uncertainty as faithfully as possible; the main characteristics of such a theory are outlined in section 3 (see also Koutsoyiannis *et al.*, 2007).

While a nonstationary description of climate is difficult to establish or infeasible, in other cases, related to water resources, it may be much more meaningful. For example, in modelling of streamflow downstream of a dam we would use a nonstationary model with a shift in the statistical characteristics before and after the construction of the dam. Gradual changes in the flow regime, e.g., due to urbanization that evolves in time, could also justify a nonstationary description, provided that a solid information or knowledge (as opposed to ignorance) of the agents affecting a hydrological process is available. Even in such cases, as far as modelling of future conditions is concerned, a stationary model of the future is sought most frequently. A procedure that could be called "stationarization" is then necessary to adapt the past observations to the future conditions. For example, the flow data prior to the construction of the dam could be properly adapted, by deterministic modelling, so as to determine what the flow would be if the dam existed. Also, the flow data at a certain phase of urbanization could be adapted so as to represent the future conditions of urbanization. Such adaptations enable building a stationary model of the future.

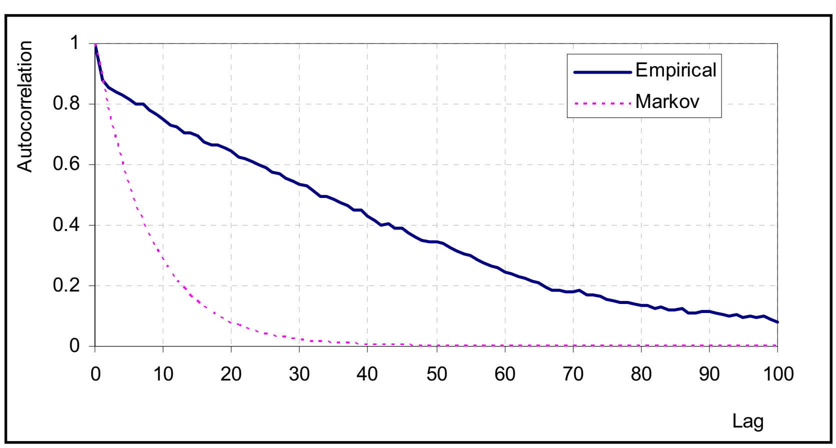

Figure 6. Empirical autocorrelogram of the time series of Figure 3 in comparison to the theoretical autocorrelogram of a Markovian process with lag one autocorrelation equal to the empirical.

Change Under Stationarity and the Hurst-Kolmogorov Dynamics

It was asserted earlier that nonstationarity is not synonymous to change. Even in the simplest stationary process, the white noise, there is change all the time. But in this case, which is characterized by independence in time, the change is only short-term. There is no change of long-term time averages. However, a process with dependence in time exhibits longer-term changes. Thus, change is tightly linked to dependence and long-term change to long-range dependence. Hence, stochastic concepts that have been devised to study dependence also help us to study change.

Here we remind of three such concepts, or stochastic tools, stressing that all are meaningful only for stationary processes (albeit this is sometimes missed). The autocorrelogram, which is a plot of the autocorrelation coefficient vs. lag time, provides a very useful characterization and visualization of dependence. Figure 6 depicts the empirical autocorrelogram estimated from the 1000 items of the time series of Figure 3. The fact that the autocorrelation is positive even for lags as high as 100 is an indication of long-range dependence. The classical Markovian dependence would give much lower autocorrelation coefficients, as also shown in Figure 6, whereas a white noise process would give zero autocorrelations, except in lag 0, which is always 1 irrespectively of the process. We recall that the process in our example involves no "memory" mechanism; it just involves change in two characteristic scales, 1 (the white noise components) and 50 (the average length of the plateaus). Thus, interpretation of long-range dependence as "long memory", despite being very common, is misleading; it is more insightful to interpret long-range dependence as long-term change (this has been first pointed out—or implied—by Klemes, 1974).

The power spectrum, which is the inverse finite Fourier transform of the autocorrelogram, is another stochastic tool for the characterization of change with respect to frequency. The power spectrum of our example is shown in Figure 7, where a rough line appears, which has an overall slope of about −1. This negative slope, which indicates the importance of variation at lower frequencies relative to the higher ones, provides a clue of long-range dependence. However, the high roughness of the power spectrum does not allow accurate estimations. A better depiction is provided in Figure 8 by the climacogram (from the Greek climax, i.e., scale), which provides a multi-scale stochastic characterization of the process. Based on the process $\underline{x}_i$ at scale 1, we define a process $\underline{x}_i^{(k)}$ at any scale $k \geq 1$ as:

$$\underline{x}_i^{(k)} := \frac{1}{k} \sum_{l=(i-1)k+1}^{ik} \underline{x}_l \qquad (1)$$

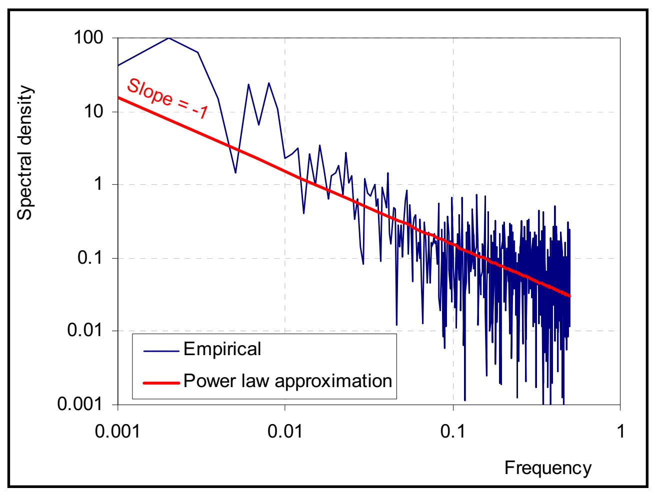

Figure 7. Empirical power spectrum of the time series of Figure 3.

A key multi-scale characteristic is the standard deviation $\sigma^{(k)}$ of $\underline{x}_i^{(k)}$. The climacogram is a plot (typically double logarithmic) of $\sigma^{(k)}$ as a function of the scale $k \geq 1$. While the power spectrum and the autocorrelogram are related to each other through a Fourier transform, the climacogram is related to the autocorrelogram by a simpler transformation, i.e.,

$$\sigma^{(k)} = \frac{\sigma}{\sqrt{k}}\sqrt{\alpha_k}\,, \quad \alpha_k = 1 + 2\sum_{j=1}^{k-1}\left(1-\frac{j}{k}\right)\rho_j \quad \text{<-->} \quad \rho_j = \frac{j+1}{2}\alpha_{j+1} - j\alpha_j + \frac{j-1}{2}\alpha_{j-1} \qquad (2)$$

To estimate the climacogram, the standard deviation $\sigma^{(k)}$ could be calculated either from the autocorrelogram by means of (2) or directly from time series $\underline{x}_i^{(k)}$ aggregated by (1). It is readily verified (actually this is the most classical statistical law) that in a white noise process, $\sigma(k) = \sigma/\sqrt{k}$, which implies a slope of −1/2 in the climacogram. Positively autocorrelated processes yield higher $\sigma^{(k)}$ and perhaps milder slopes of the climacogram. Figure 8 illustrates the constant slope of −1/2 of a white-noise process, which is also asymptotically the slope of a Markovian process, while the process of our example suggests a slope of –0.25 for scales k near 100.

Recalling that our example involves two time scales of change (1 and 50), we can imagine a process with additional time scales of change. The simplest case of such a process (which assumes theoretically infinite time scales of fluctuation, although practically, three such scales suffice; Koutsoyiannis, 2002), is the one whose climacogram has a constant slope $H-1$, i.e.

$$\sigma^{(k)} = k^{H-1}\sigma \qquad (3)$$

This simple process, which is essentially defined by (3), has been termed the Hurst-Kolmogorov (HK) process (after Hurst, 1951, who first analyzed statistically the long-term behaviour of geophysical time series, and Kolmogorov, 1940, who, in studying turbulence, had proposed the mathematical form of the process, also known as simple scaling stochastic model or fractional Gaussian noise). The constant H is called the Hurst coefficient and in positively-dependent processes ranges between 0.5 and 1. The elementary statistical properties of the HK process are shown in Table 1, where it can be seen that all properties appear to be power laws of scale, lag and frequency.

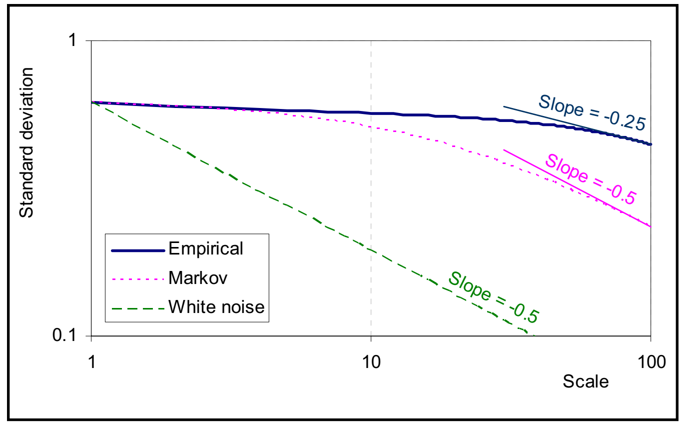

Figure 8. Empirical climacogram of the time series of Figure 3 in comparison to the theoretical climacograms of a white-noise and a Markovian process.

Figure 9. Development of turbulence in a hydraulic jump in a controlled experiment in laboratory, whose window, with the help of reader's imagination, reveals the outer uncontrolled turbulence (courtesy of Panos Papanicolaou).

Fluctuations at multiple temporal or spatial scales, which may suggest HK stochastic dynamics, are common in Nature. One characteristic example for visualization is the hydraulic jump shown in Figure 9. In this case we have molecular motion or change, as well as micro-turbulence, because the Reynolds number is high; downstream of the hydraulic jump (in the right part of the photo), we have also macro-turbulence, i.e., turbulence at larger scales. The energy associated with each scale increases with scale length (e.g., without the macro-turbulence of the hydraulic jump, the energy loss due to molecular motion and micro-turbulence would be much lower).

We owe the most characteristic example of a large spatial-scale phenomenon that exhibits HK temporal dynamics to the Nilometer time series, the longest available instrumental record. Figure 10 shows the record of the Nile minimum water level from the 7th to the 15th century AD (813 years). Comparing this Nilometer time series with synthetically generated white noise, also shown in Figure 10 (lower panel), we clearly see a big difference on the 30-year scale. The fluctuations in the real-world process are much more intense and frequent than the stable curve of the 30-year average in the white noise process. The climacogram of the Nilometer series, shown in Figure 11, suggests that the HK model is a very good

Statistical property	At scale k = 1 (e.g. annual)	At any scale k
Standard deviation	$\sigma \equiv \sigma^{(1)}$	$\sigma^{(k)} = k^{H-1}\sigma$
Autocorrelation function (for lag j)	$\rho_j \equiv \rho_j^{(1)} = \rho_j^{(k)} \approx H(2H-1)\lvert j\rvert^{2H-2}$	
Power spectrum (for frequency ω)	$s(\omega) \equiv s^{(1)}(\omega) \approx 4(1-H)\sigma^2(2\omega)^{1-2H}$	$s^{(k)}(\omega) \approx 4(1-H)\sigma^2 k^{2H-2}(2\omega)^{1-2H}$

Table 1. Elementary statistical properties of the HK process

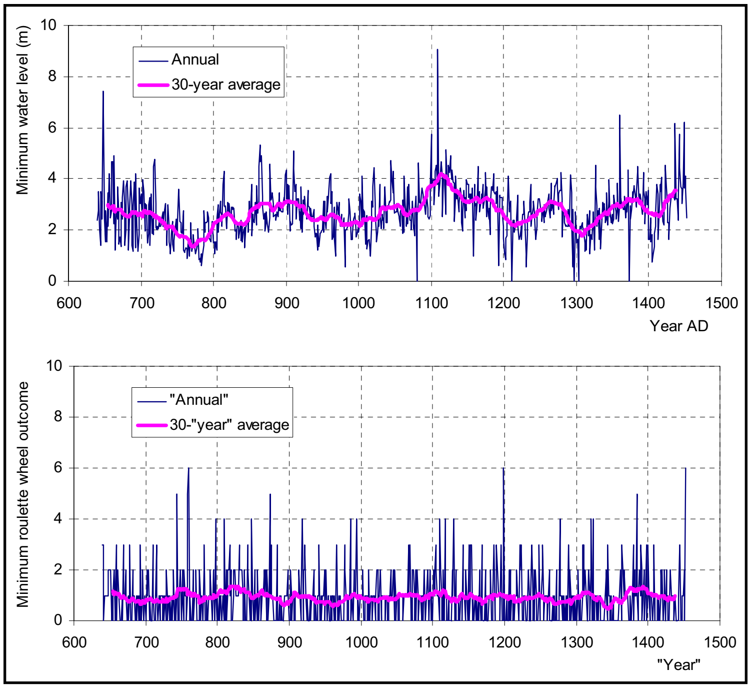

Figure 10. The annual minimum water level of the Nile River from the Nilometer (upper) and, for comparison, a synthetic series, each value of which is the minimum of 36 outcomes of a roulette wheel (lower); both time series have equal standard deviation (about 1.0).

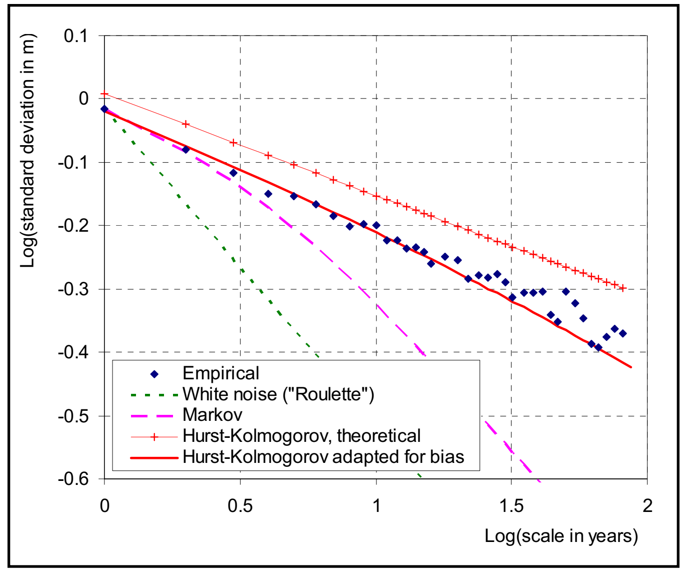

Figure 11. Climacogram of the Nilometer time series of Figure 10.

True values →	Mean, μ	Standard deviation, σ	Autocorrelation ρ_l for lag l
Standard estimator	$\underline{\bar{x}} := \frac{1}{n}\sum_{i=1}^{n} \underline{x}_i$	$\underline{s} := \sqrt{\frac{1}{n-1}}\sqrt{\sum_{i=1}^{n} (\underline{x}_i - \underline{\bar{x}})^2}$	$\underline{r}_l := \frac{1}{(n-1)\underline{s}^2} \cdot \sum_{i=1}^{n-l} (\underline{x}_i - \underline{\bar{x}})(\underline{x}_{i+l} - \underline{\bar{x}})$
Relative bias of estimation, CS	0	≈ 0	≈ 0
Relative bias of estimation, HKS	0	$\approx \sqrt{1 - \frac{1}{n'}} - 1 \approx -\frac{1}{2n'}$ (–22%) (–22%)	$\approx -\frac{1/\rho_l - 1}{n' - 1}$ (–79%)
Standard deviation of estimator, CS	$\frac{\sigma}{\sqrt{n}}$ (10%)	$\approx \frac{\sigma}{\sqrt{2(n-1)}}$ (7.1%)	
Standard deviation of estimator, HKS	$\frac{\sigma}{\sqrt{n'}}$ (63%)	$\approx \frac{\sigma\sqrt{(0.1\,n + 0.8)^{\lambda(H)}(1 - n^{2H-2})}}{\sqrt{2(n-1)}}$ where $\lambda(H) := 0.088\,(4H^2 - 1)^2$ (9.3%)	

Table 2. Impacts to statistical estimation: Hurst-Kolmogorov statistics (HKS) vs. classical statistics (CS) (sources: Koutsoyiannis, 2003; Koutsoyiannis and Montanari, 2007).

Notes (a) $n' := n^{2-2H}$ is the "equivalent" or "effective" sample size: a sample with size n' in CS results in the same uncertainty of the mean as a sample with size n in HKS; (b) the numbers in parentheses are numerical examples for n = 100, σ = 1, H = 0.90 (so that n′ = 2.5) and l = 10.

representation of reality. The Hurst coefficient is $H = 0.84$ and the same value is verified from the simultaneous record of maximum water levels and from the modern record (131 years) of the Nile flows at Aswan.

The same behaviour can be verified is several geophysical time series; examples are given in most related publications referenced herein. Two additional examples are depicted in Figure 12, which refers to the monthly lower tropospheric temperature, and in Figure 13, which refers to the monthly Atlantic Multidecadal Oscillation (AMO) index. Both examples suggest consistency with HK behaviour with a very high Hurst coefficient, $H = 0.99$.

One of the most prominent implications of the HK behaviour concerns the typical statistical estimation. The HK dynamics implies dramatically higher intervals in the estimation of location statistical parameters (e.g., mean) and highly negative bias in the estimation of dispersion parameters (e.g., standard deviation). The HK framework allows calculating the statistical measures of bias and uncertainty of statistical parameters, as summarized in Table 2, and even of future predictions (Koutsoyiannis *et al.*, 2007). It is thus striking that in most of the literature the HK behaviour is totally neglected and even studies recognizing the presence of HK dynamics usually miss to account for these implications in statistical estimation and testing.

Naturally, the implications magnify as the “intensity” of the HK behaviour increases, i.e., as H approaches 1. Table 2 provides, in addition to the theoretical formulae, a numerical example for $n = 100$ and $H = 0.90$, whereas Figure 12 and Figure 13 depict the huge bias in the standard deviation when $H = 0.99$. This bias increases with increased time scale because the sample size for higher time scales becomes smaller. Obviously, the comparison of the sample standard deviation, estimated by the classical statistical estimator, with the theoretical one of the HK model must be done after subtraction of the bias from the latter.

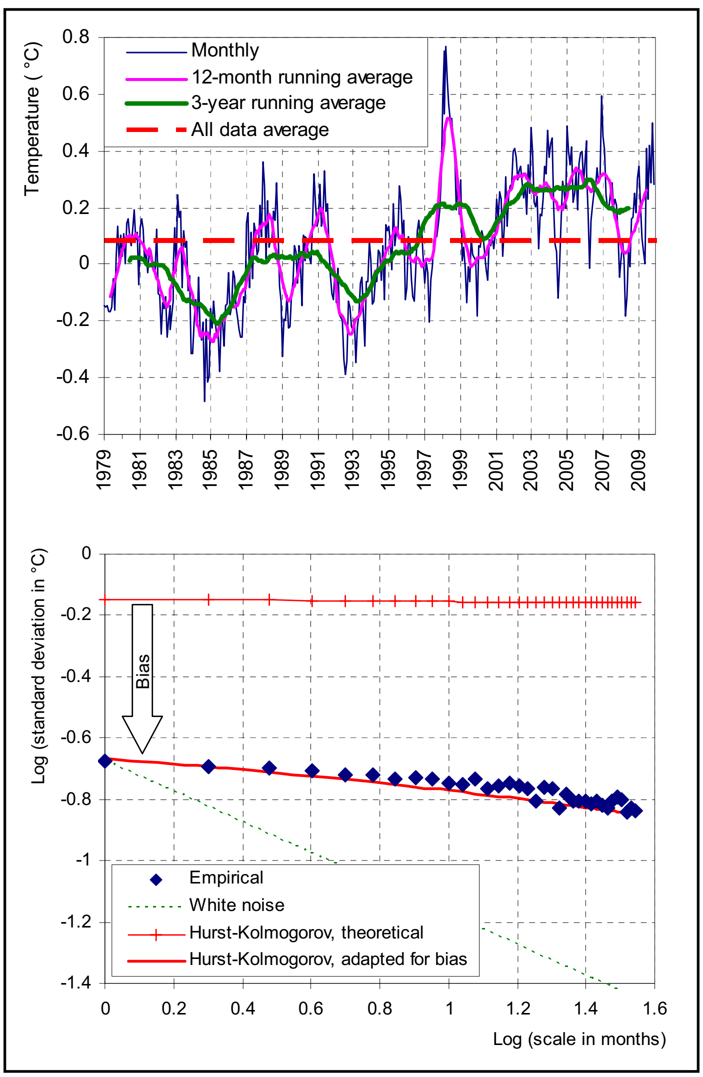

Figure 12. Monthly time series (upper) and climacogram (lower) of the global lower tropospheric temperature (data for 1979-2009, from http://vortex.nsstc.uah.edu/public/msu/t2lt/tltglhmam_5.2).

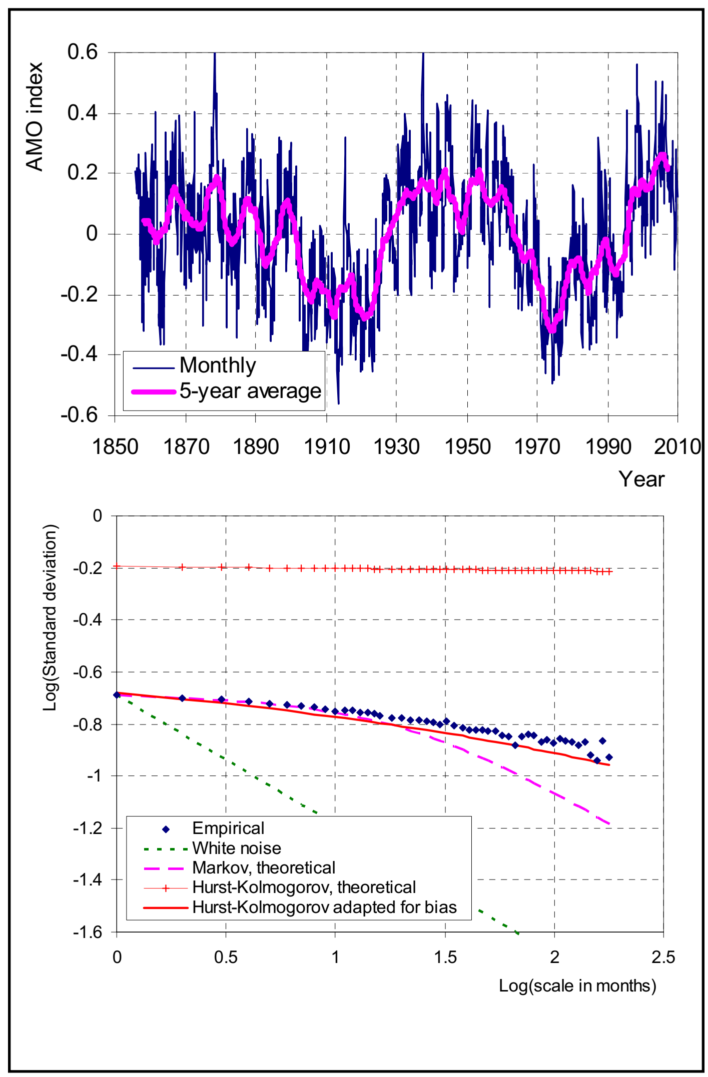

Figure 13. Monthly time series (upper) and climacogram (lower) of the Atlantic Multidecadal Oscillation (AMO) index (data for 1856-2009, from NOAA, http://www.esrl.noaa.gov/psd/data/timeseries/AMO/).

Implications in engineering design and water resources management

Coming back to the Athens water supply system, it is interesting to estimate the return period of the multi-year drought mentioned in the Introduction. Assuming that the annual runoff in the Boeoticos Kephisos basin can be approximated by a Gaussian distribution and that the multi-year standard deviation at scale (number of years) k is given by the classical statistical law, $\sigma^{(k)} = \sigma/\sqrt{k}$, we can easily assign a theoretical return period to the lowest (as well as to the highest) recorded value for each time scale. Figure 14 shows the assigned return periods of the lowest and highest values for time scales $k = 1$ to 10. Empirically, since the record length is about 100 years, we expect that the return period of lowest and highest values would be of the order of 100 years for all time scales. This turns out to be true for $k = 1$ to 2, but the return periods reach 10,000 years at scale $k = 5$. Furthermore, the return period of the lowest value at scale $k = 10$ (10-year drought) reaches 100,000 years!

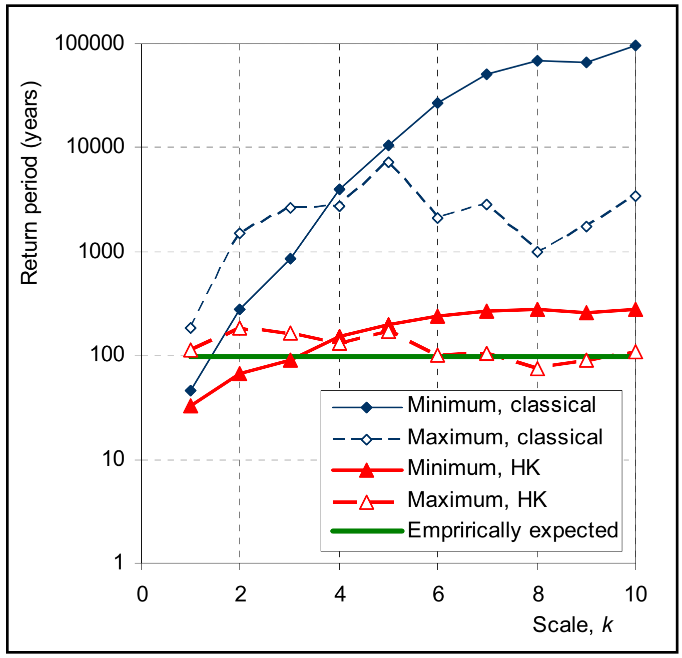

Figure 14. Return periods of the lowest and highest observed annual runoff, over time scale k = 1 to 10 years, of the Boeoticos Kephisos basin assuming normal distribution (adapted from Koutsoyiannis et al., 2007).

Is this sufficient evidence that Athens experienced a very infrequent drought event, which happens on the average once every 100,000 years, in our lifetime? In the initial phase of our involvement in this case study we were inclined to believe that we witnessed an event that extraordinary, but gradually, we understood that the answer should be negative. History is the key to the past, to the present, and to the future; and the longest available historical record is that of the Nilometer (Figure 10). This record offers a precious empirical basis of long-term changes. It suffices to compare the time series of the Beoticos Kephisos runoff (shown in its entirety in Figure 15) with that of the Nilometer series. We observe that a similar pattern had appeared in the Nile flow between 680 and 780 AD: a 100-year falling trend (which, notably, reverses after 780 AD), with a clustering of very low water level around the end of this period, between 760 and 780 AD. Such clustering of similar events was observed in several geophysical time series by Hurst (1951), who stated: "*Although in random events groups of high or low values do occur, their tendency to occur in natural events is greater. This is the main difference between natural and random events.*"

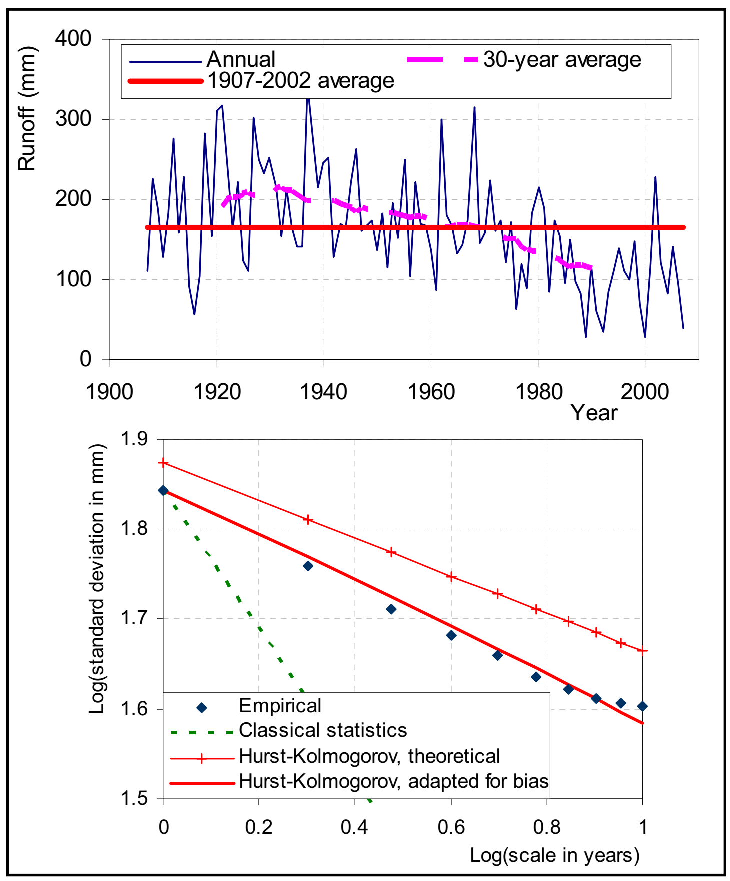

Figure 15. The entire annual time series (upper) and the climacogram (lower) of the Boeoticos Kephisos runoff.

Thus, the Athens story simply tells us that we should replace the classical statistical framework with a HK framework. As shown in Figure 15 (lower panel) the Boeticos Kephisos runoff time series is consistent with the HK model, with a Hurst coefficient $H = 0.79$. Redoing the calculations of return period, we find that the return period for scale k reduces from the extraordinary value of 100,000 years to a humble value of 270 years. Also, the HK framework renders the observed downward trend a natural and usual behaviour (Koutsoyiannis, 2003). The Boeticos Kephisos runoff is another "naturally trendy" process (Cohn and Lins, 2005).

Thus, the HK framework implies a perspective of natural phenomena that is very different from that of classical statistics, particularly in aggregate scales. This is further demonstrated in Figure 16, which depicts normal probability plots of the distribution quantiles of the Boeoticos Kephisos runoff at the annual and the climatic, 30-year, time scale. At the annual time scale (k = 1) the classical and the HK statistics yield the same point estimates of distribution quantiles (i.e. the same amount of uncertainty due to variability), but the estimation (or parameter) uncertainty, here defined by the 95% confidence limits constructed by a Monte Carlo method, is much greater according to the HK statistics. The confidence band is narrow in classical statistics (shaded area in Figure 16) and becomes much wider in the HK case. More interesting is the lower panel of Figure 16, which refers to the typical climatic time scale (k = 30). The low variability and uncertainty in the classical model is depicted as a narrow, almost horizontal, band in the lower panel of Figure 16. Here, the HK model, in addition to the higher parameter uncertainty, results in uncertainty due to variability much wider than in the classical model. As a result, while the total uncertainty (by convention defined as the difference of the upper confidence limit at probability of exceedence 97.5% minus the lower confidence limit at probability of exceedence 2.5%) is about 50% of the mean in the classical model, in the HK case it becomes about 200% of the mean, or four times larger. Interestingly, it happens that the total uncertainty of the classical model *at the annual scale* is 200% of the mean. In other words, the total uncertainty (due to natural variability and parameter estimation) at the annual level according to the classical model equals the total uncertainty at the 30-year scale according to HK model. This allows paraphrasing a common saying (which sometimes has been used to clarify the definition of climate, e.g., NOAA Climate Prediction Center, 2010) that "*climate is what we expect, weather is what we get*" in the following way: "*weather is what we get immediately, climate is what we get if you keep expecting for a long time*".

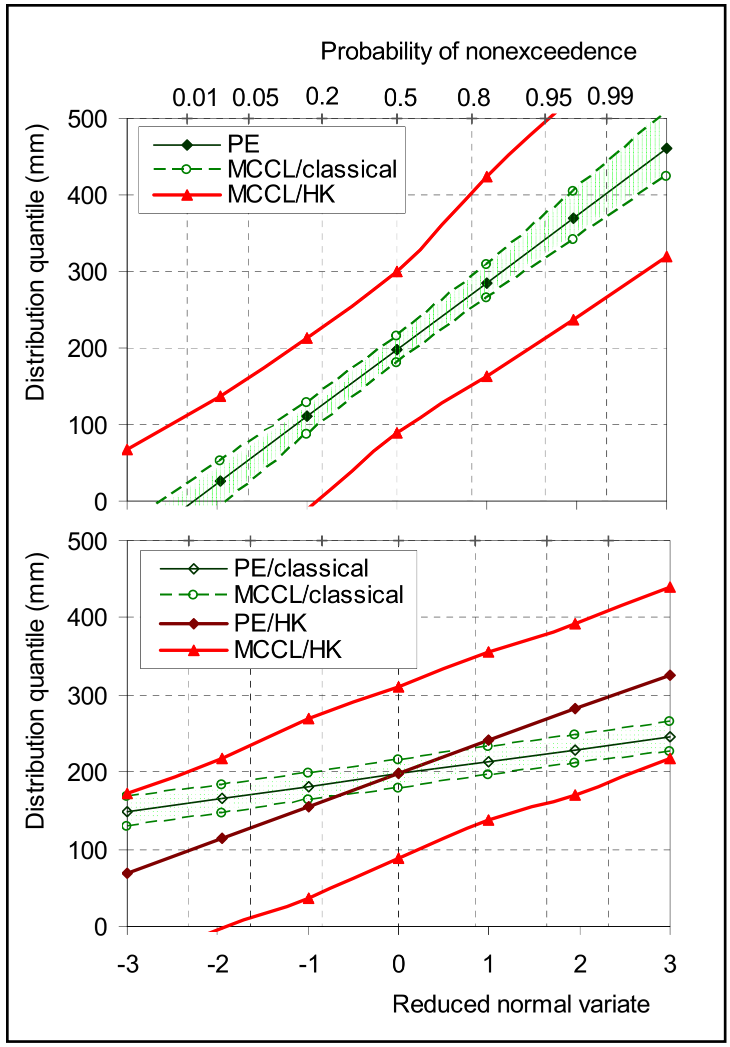

Figure 16. Point estimates (PE) and 95% Monte Carlo confidence limits (MCCL) of the distribution quantiles of the Boeoticos Kephisos runoff at the annual (upper) and climatic (30-year; lower) time scales, both for classical and HK statistics (adapted from Koutsoyiannis et al., 2007).

For reasons that should be obvious from the above discussion, the current planning and management of the Athens water supply system are based on the HK framework. Appropriate multivariate stochastic simulation methods have been developed (Koutsoyiannis, 2000, 2001) that are implemented within a general methodological framework termed parameterization-simulation-optimization (Nalbantis and Koutsoyiannis, 1997; Koutsoyiannis and Economou, 2003; Koutsoyiannis *et al.*, 2002, 2003; Efstratiadis *et al.*, 2004). The whole framework assumes stationarity, but simulations always use the current initial conditions (in particular, the current reservoir storages) and the recorded past conditions: apparently, in a Markovian framework, only the latest observations affect the future probabilities, but in the non-Markovian HK framework the entire record of past observations should be taken into account to condition the simulations of future (Koutsoyiannis, 2000).

Nonetheless, it is interesting to discuss two alternative methods that are more commonly used than the methodology developed for Athens. The first alternative approach, which is nonstationary, consists of the projection of the observed "trend" into the future. As shown in Figure 17, according to this approach the flow would disappear by 2050. Also this approach would lead to reduced uncertainty (because it assumes that the observed "trend" explains part of variability); the initial standard deviation of 70 mm would decrease to 55 mm. Both these implications are glaringly absurd.

The second alternative, again admitting nonstationarity, is to use outputs of climate models and to feed them in hydrological models to predict the future runoff. This approach is illustrated in Figure 18, also in comparison to the HK stationary approach and the classical statistical approach. Outputs from three different GCMs (ECHAM4/OPYC3, CGCM2, HadCM3), each one for two different scenarios, were used, thus shaping 6 combinations shown in the legend of Figure 18 (each line of which corresponds to each of the three models in the order shown above; see more details in Koutsoyiannis *et al.*, 2007). To smooth out the annual variability, the depictions of Figure 18 refer to the climatic (30-year) scale.

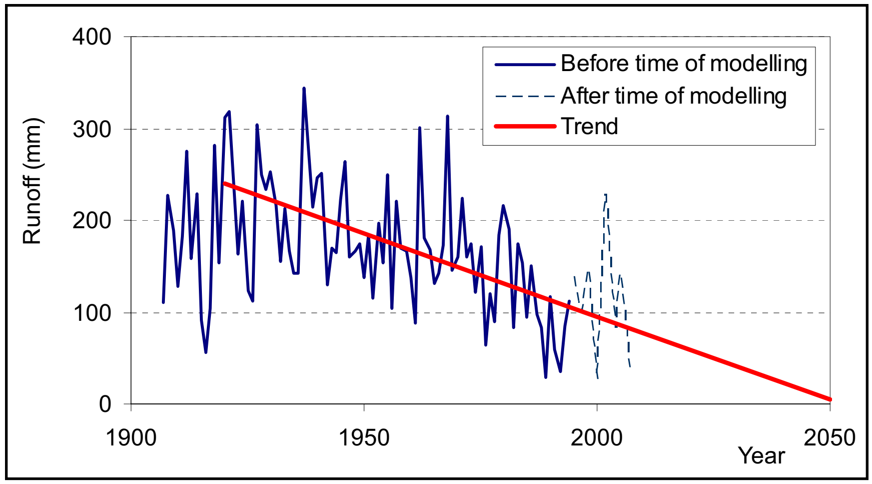

Figure 17. Illustration of the alternative method of trend projection into the future for modelling of the Boeoticos Kephisos runoff.

In fact, outputs of the climate models exhibited huge departures from reality (highly negative efficiencies at the annual time scale and above); thus, adjustments, also known as "statistical downscaling", were performed to make them match the most recent observed climatic value (30-year average). Figure 18 shows plots of the GCM-based time series after the adjustments. For the past, despite adjustments, the proximity of models with reality is not satisfactory (they do not capture the falling trend, except one part reflecting the more intense water resources exploitation in recent years). Even worse, the future runoff obtained by adapted GCM outputs is too stable. All different model trajectories are crowded close to the most recent climatic value. Should one attempt to estimate future uncertainty by enveloping the different model trajectories, this uncertainty would be lower even from that produced by the classical statistical model. Hence, the GCM-based approach is too risky, as it predicts a future that is too stable, whereas the more consistent HK framework entails a high future uncertainty (due to natural variability and unknown parameters), which is also shown in Figure 18. The planning and management of the Athens water supply system is based on the latter uncertainty.

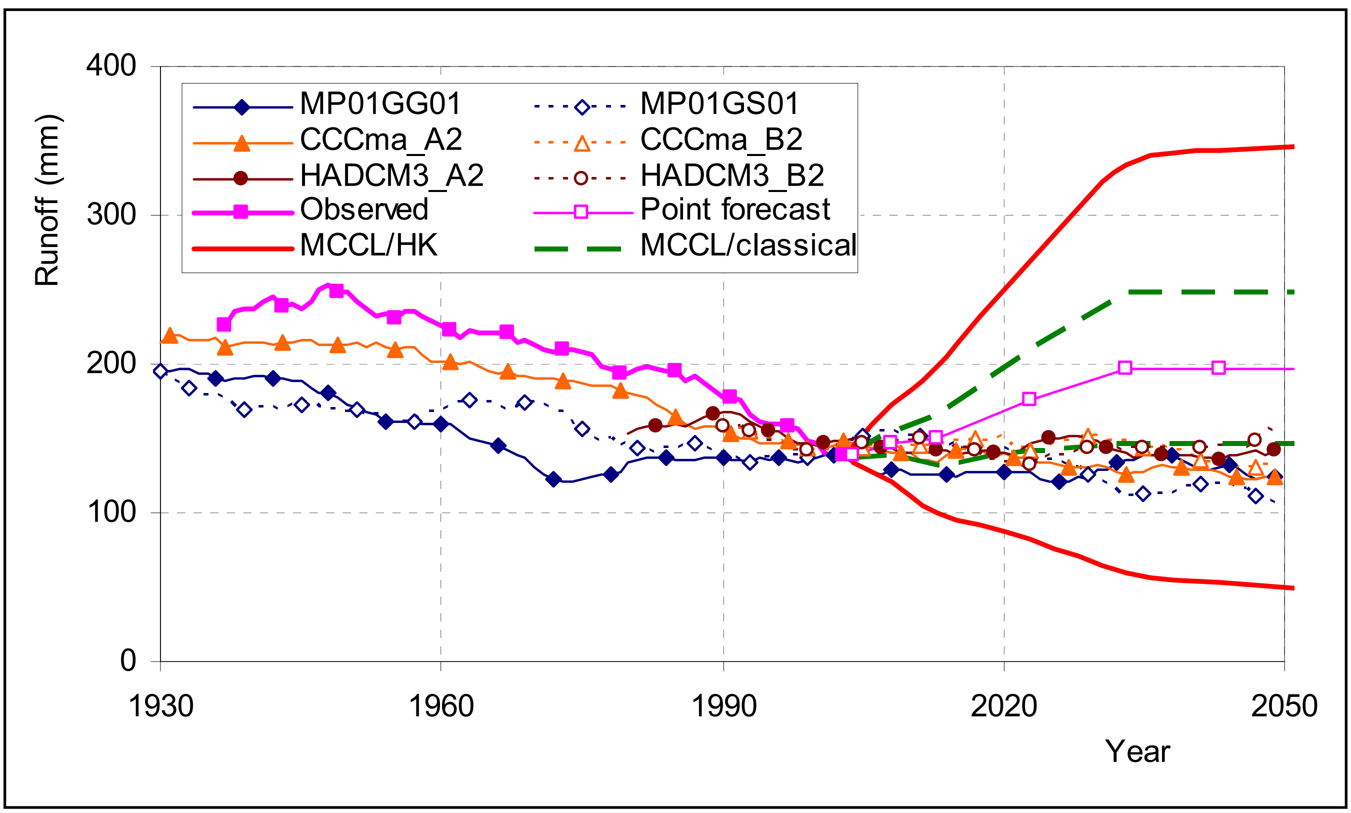

Figure 18. Illustration the alternative GCM-based method for modelling of the Boeoticos Kephisos runoff, vs. the uncertainty limits (Monte Carlo Confidence Limits—MCCL) estimated for classical and HK statistics; runoff is given at climatic scale, i.e. runoff y at year x is the average runoff of a 30-year period ending at year x (adapted from Koutsoyiannis et al., 2007).

Additional Remarks

While this exposition has focused on climatic averages and low extremes (droughts), it may be useful to note that change, which underlies the HK dynamics, also affects high extremes such as intense storms and floods. This concerns both the marginal distribution tail as well as the timing of high intensity events. For example, Koutsoyiannis (2004) has shown that an exponential distribution tail of rainfall may shift to a power tail if the scale parameter of the former distribution changes in time; and it is well known that a power tail yields much higher rainfall amounts in comparison to an exponential tail for high return periods. Also, Blöschl and Montanari (2010) demonstrated that five of the six largest floods of the Danube at Vienna (100 000 km^2 catchment area) of the 19th century were grouped in its last two decades. This is consistent with Hurst's observation about grouping of similar events and should properly be taken into account in flood management—rather than trying to speculate about human-induced climate effects. (Interestingly, Blöschl and Montanari, by plotting the 19th century peak flows in a separate graph so that the grouping appear as if it indeed were in "the last two decades", try to tease the recent "trend" to regard the most recent hydroclimatic phenomena as extraordinary and human induced).

Overall, the "new" HK approach exposed herein is as old as Kolmogorov's (1940) and Hurst's (1951) expositions. It is stationary (not nonstationary) and demonstrates how stationarity can coexist with change at all time scales. It is linear (not nonlinear) thus emphasizing the fact that stochastic dynamics need not be nonlinear to produce realistic trajectories (while, in contrast, trajectories from linear deterministic dynamics are not representative of the evolution of complex natural systems). The HK approach is simple, parsimonious, and inexpensive (not complicated, inflationary and expensive) and is honest (not deceitful) because it does not hide uncertainty and it does not pretend to predict the distant future deterministically.

Conclusions

- Change is nature's style.
- Change occurs at all time scales.
- Change is not nonstationarity.
- Hurst-Kolmogorov dynamics is the key to perceive multi-scale change and model the implied uncertainty and risk.
- In general, the Hurst-Kolmogorov approach can incorporate deterministic descriptions of future changes, if available.
- In the absence of credible predictions of the future, Hurst-Kolmogorov dynamics admits stationarity.

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Biography

Demetris Koutsoyiannis received his diploma in Civil Engineering from the National Technical University of Athens (NTUA) in 1978 and his doctorate from NTUA in 1988. Currently, he is professor of the NTUA in Hydrology and Analysis of Hydrosystems; also professor of Hydraulics in the Hellenic Army's Postgraduate School of Technical Education of Officers Engineers; Editor of Hydrological Sciences Journal; member of the editorial board of Hydrology and Earth System Sciences, and formerly of Journal of Hydrology and Water Resources Research; and Chair of the Sub-Division on Precipitation & Climate of the Division on Hydrological Sciences of the European Geosciences Union (EGU). He received the Henry Darcy Medal in 2009 by EGU for his outstanding contributions to the study of hydrometeorological variability and to water resources management. He teaches undergraduate and postgraduate courses in hydrometeorology, hydrology, hydraulics, hydraulic works, water resource systems, water resource management, and stochastic modelling. He is an experienced researcher in the areas of hydrological modelling, hydrological stochastics, climate stochastics, analysis of hydrosystems, water resources engineering and management, hydroinformatics, and ancient hydraulic technologies. He has participated in over 40 research projects and 60 engineering studies as a consultant. His record includes more than 500 scientific and technological contributions (research articles, books and educational notes, conference and workshop talks, research reports, engineering studies and miscellaneous publications), among which 74 publications in peer reviewed journals. (More information: http://www.itia.ntua.gr/dk/)

Analysis of the Stationarity of Flood Peaks in the United States

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Abstract

Annual maximum peak discharge time series from 196 stream gage stations with a record of at least 75 years from the Midwest U.S. are examined to study flood peak distributions from a regional point of view. The focus of this study is to evaluate: i) "mixtures" of flood peak distributions, ii) upper tail and scaling properties of the flood peak distributions and iii) presence of temporal nonstationarities in the flood peak records. Warm season convective systems are responsible for some of the largest floods in the area, in particular in Nebraska, Kansas, and Iowa. Spring events associated with snowmelt and rain-on-snow are common in the northern part of the study domain. Non-parametric tests are used to investigate the presence of abrupt and slowly varying changes. Change-points rather than linear trends are responsible for most violations of the stationarity assumption. The abrupt changes in flood peaks can be associated with anthropogenic changes, such as changes in land use and land cover, agricultural practice and construction of dams. The trend analyses do not suggest an increase in the flood peak distribution due to anthropogenic climate change. Examination of the upper tail and scaling properties of the flood peak distributions are examined by means of the location, scale, and shape parameters of the Generalized Extreme Value (GEV) distribution.

Introduction

The Upper Midwest U.S. (in this study it includes North Dakota, South Dakota, Nebraska, Kansas, Minnesota, Iowa, Missouri, Wisconsin, Illinois) has been plagued by flooding over the past 100 years. These events are responsible for numerous fatalities and large economic damage (e.g., Changnon, 1997, 1999; Pielke and Downton, 2000). Detailed analyses of the flood peak records will allow for a better insight into the different flood-generating mechanisms, and a better understanding of possible changes in the flood peak records during the twentieth century. This study focuses on: i) "mixtures" of flood peak distributions, ii) the investigation of upper tail and scaling properties of flood peak distributions and iii) the presence of temporal nonstationarities in the flood peak records. To address these questions we use annual maximum flood peak records from 196 U.S. Geological Survey (USGS) stream gage stations with a record of at least 75 years over the Midwest U.S.

The flood events are associated with distinctive hydrometeorological settings, such as spring flood events related to snow melt and summer floods associated with organized convective systems. For these reasons, we study the flood peak distributions in terms of "mixtures" of different generating mechanisms (e.g., Waylen and Woo, 1982; Rossi et al., 1984; Hirschboeck, 1987; Waylen, 1991; Olsen et al., 1999; Murphy, 2001; Morrison and Smith, 2002; Alila and Mtiraoui, 2002; Villarini and Smith, 2010). Summertime convective systems are a special focus of this study, given the large impact they have on flood hazards for this region.

The Generalized Extreme Value (GEV) distribution (e.g., Coles, 2001) is used as the framework for the examination of the upper tail and scaling properties of the flood peak distribution. The GEV is supported by extreme value theory but other formulations have been used for modeling the flood peak distributions (e.g., Moon and Lall, 1994; Adamowski, 2000; Kim and Heo, 2002; Kidson and Richards, 2005). For the eastern U.S., Villarini and Smith (2010) showed that the upper tail properties of the flood peak distribution exhibited large spatial heterogeneity, with very large values of the shape parameter (it controls the heaviness of the tail of the distribution) corresponding to stations in the Appalachian mountains. They also showed that land falling tropical cyclones were responsible for the large values of the shape parameter, and that the parameters of the GEV distribution scaled with drainage area.

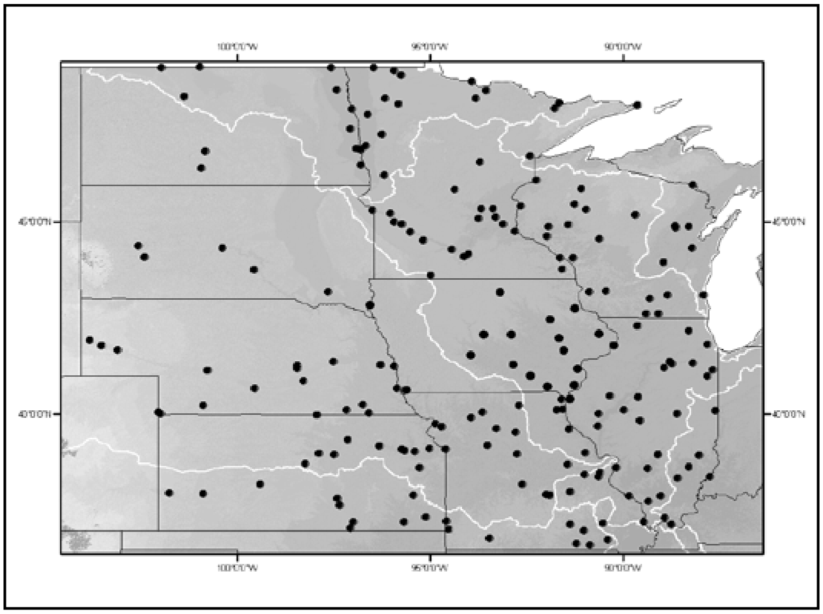

Figure 1. Map showing the location of the USGS stream gage stations with a record of at least 75 years included in this study.

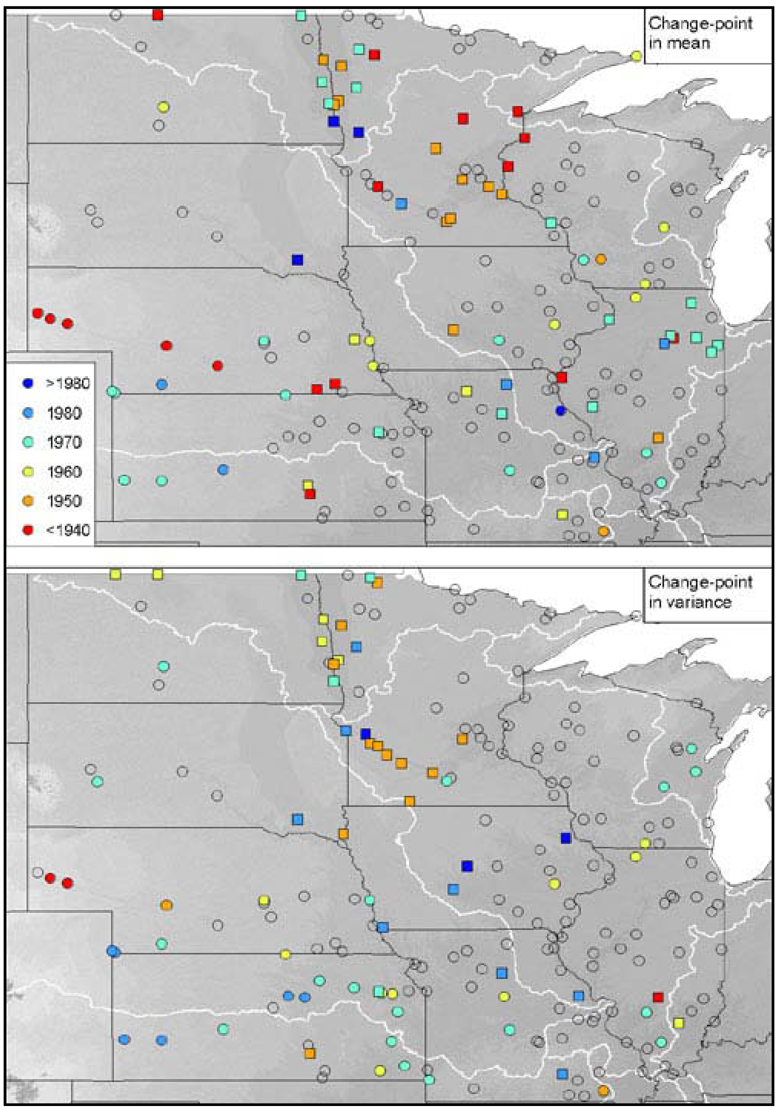

Figure 2. Maps with the location of the stations with a change-point in mean (upper panel) and variance (bottom panel) significant at the 5% level. The circle indicates a decrease in mean or variance after the change-point, while the squares an increase. The empty symbols indicate the lack of a statistically significant change-point. These results are based on the Pettitt test.

One issue that has been the object of a growing number of studies is the validity of the stationarity assumption. The validity of this assumption has been recently challenged (Milly et al., 2008) and novel approaches to address the risks associated with a continuously changing flood frequency distribution should be developed (see Villarini et al. (2009b) for a recent discussion). The annual flood peak time series is stationary if the distribution is invariant under translation in time (Brillinger, 2001). This means they are free of periodicities, abrupt and slowly varying changes (e.g., Salas, 1993). For an extensive discussion about the notion of stationarity in hydrology, the interested reader is pointed to Matalas (1997) and Koutsoyiannis (2006). Contrasting results have been found concerning the validity of the stationarity assumption for the annual maximum flood peaks in the continental U.S. (Changnon and Kunkel, 1995; Lins and Slack, 1999; Douglas et al., 2000; Groisman et al., 2001, 2004; McCabe and Wolock, 2002; USGS, 2005; Villarini et al., 2009a; Villarini and Smith, 2010). In this region, some studies found mostly increasing trends (e.g., Changnon and Demissie, 1996; Olsen et al., 1999; Novotny and Stefan, 2007; Pinter et al., 2008; Hejazi and Markus, 2009), others mostly decreasing trends (e.g., Krug, 1996), others mixed results (e.g., Changnon and Kunkel, 1995; Gebert and Krug, 1996; Rasmussen and Perry, 2001; Lins and Slack, 2005), and others no overall trends at all (e.g., Lins and Slack, 1999; Douglas et al., 2000; Schilling and Libra, 2003; Zhang and Schilling, 2006; Villarini et al., 2009a). Recently, Villarini et al. (2009a) performed a detailed analysis of 50 USGS stations with a record of at least 100 years within the Continental U.S. They found that change-points, rather than linear trends were responsible for most violations of the stationarity assumption. Similar results were obtained by Villarini and Smith (2010) for the analysis of 572 stations with a record of at least 75 years in the eastern U.S.. The exceptional flood records maintained by the USGS (e.g., USGS, 1998; Blanchard, 2007) are instrumental for a meaningful assessment of the changes in flood frequency.

In this study we build on the work by Villarini et al. (2009a) and expand the analyses to the Midwest U.S. The validity of the stationarity assumption is checked in terms of both abrupt changes in the mean and variance of the flood peak distribution and linear trends. Abrupt changes can be caused by climatic as well as anthropogenic effects (e.g., shifts in the climate regime (e.g., Potter, 1976; Alley et al., 2003), changes in land use and land cover and construction of dams (e.g., Villarini et al. 2009a)). The non-parametric Pettitt test (Pettitt, 1979) is used to perform change-point analysis for the detection of abrupt changes in the mean and variance of the flood peak distribution. For the stations that do not present a statistically significant change-point in mean, two non-parametric tests (Mann Kendall and Spearman tests) are used to examine the presence of linear trends in the data. If a change-point in mean is detected, the time series is split into two sub-series (before and after the change-point) and the linear trend analysis is performed on each of the two sub-series (see Villarini et al. (2009a) for an extensive discussion).

The paper is organized as follows. In Section 2 we describe the data, together with a brief description of the change-point test, trend test and the GEV distribution. In Section 3 we present the results of the analyses, followed by Section 4, in which we summarize the main points and conclude the paper.

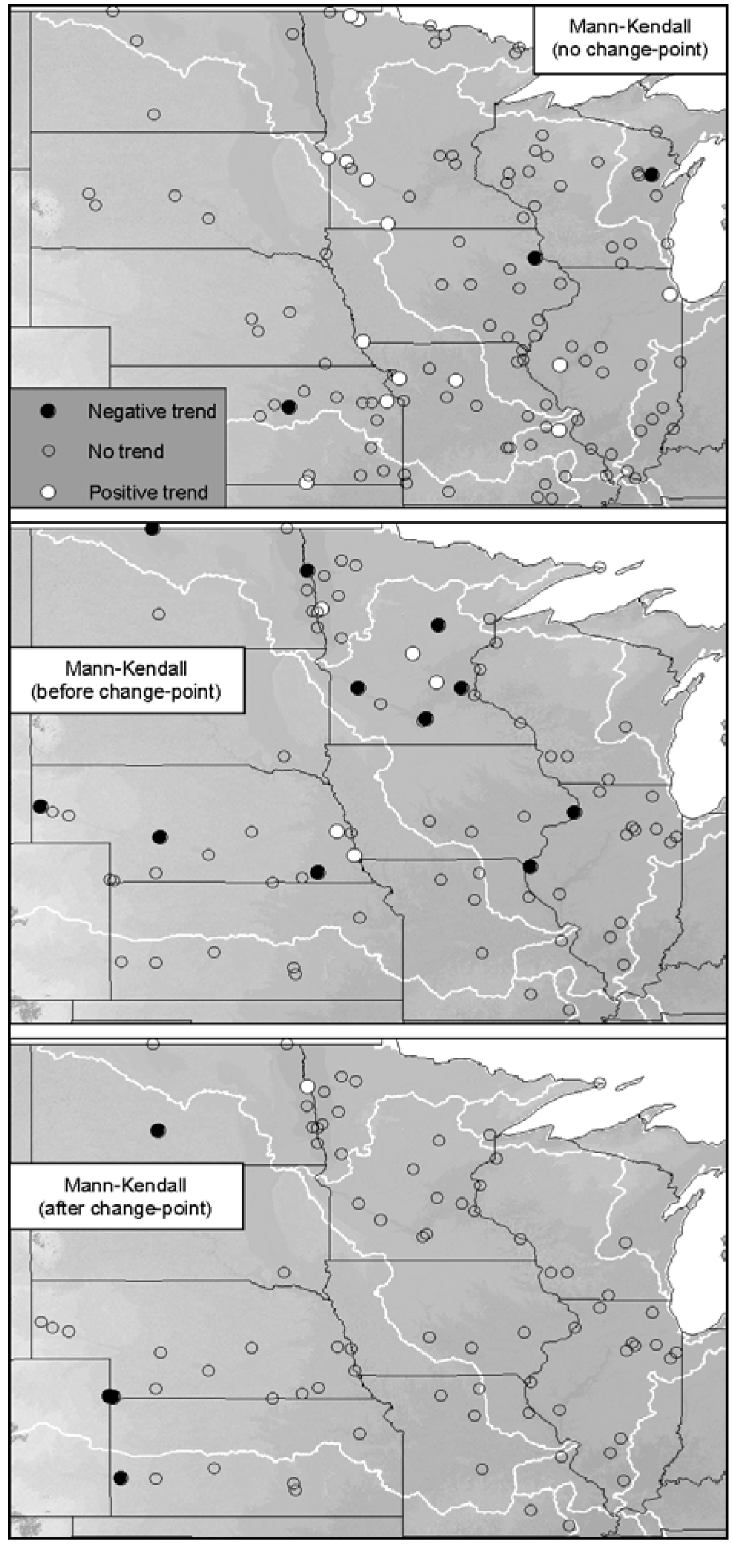

Figure 3. Maps with the results of Mann-Kendall test for the series without change-point in mean (upper panel), and with change-point in mean (middle and bottom panels). The test is significant at the 5% level.

Data and Methods

Data

In this study we consider USGS stream gage stations with a record of at least 75 years of annual maximum instantaneous peak discharge over nine states in the Midwest U.S., defined here as North Dakota, South Dakota, Nebraska, Kansas, Minnesota, Iowa, Missouri, Wisconsin and Illinois (Figure 1). Over this study domain, there are 196 stations fulfilling these requirements (12 in North Dakota, 6 in South Dakota, 18 in Nebraska, 21 in Kansas, 34 in Minnesota, 18 in Iowa, 33 in Missouri, 25 in Wisconsin, and 29 in Illinois). As shown in Figure 1, the station density is not uniform, with a larger number of stations in the eastern part of the domain (Upper Mississippi River basin) compared to the western part (Missouri River basin).

Many of the basins in this area have undergone changes in land use and land cover, agricultural practice, urbanization and construction of dams (e.g., Miller and Frink, 1984; Williams and Wolman, 1984; Hadley et al., 1987; Potter, 1991; Perry, 1994; Changnon and Demissie, 1996; Schneider, 1996; Biedenharn and Watson, 1997; Olsen et al., 1999; Kramer et al., 1999; Criss and Shock, 2001; Knox, 2001; Pegg et al., 2003; Schilling and Libra, 2003; Billington and Jackson, 2006; Zhang and Schilling, 2006; Jacobson and Galat, 2006; Novotny and Stefan, 2007; Schilling et al., 2008; Pinter et al., 2008; Mao and Cherkauer, 2009; Jacobson et al., 2009). Therefore, rather than looking for "pristine" river basins, we consider that all river basins have experienced human alteration. As shown by previous studies, this can be considered a characteristic of the U.S. flood records (Villarini et al., 2009a; Villarini and Smith, 2010). Therefore, the results of these analyses should reflect the regional impact of human activities on the flood peak distribution.

In order to evaluate whether trends in the discharge record are related to trends in extreme rainfall, we include 199 COOP rain gage stations (data from the National Climatic Data Center) with a record of at least 75 years of annual maximum daily rainfall. These stations are spread almost uniformly over the study domain and provide valuable information about the presence of changes in extreme rainfall over the region.

Change-Point and Trend Analyses

Change-point analysis is performed by means of the non-parametric Pettitt test (Pettitt, 1979). As shown in previous studies (Villarini et al., 2009a; Villarini and Smith, 2010), this test was successful in detecting abrupt changes in the mean and/or variance of the flood peak distributions (consult Rodionov (2005) and Reeves et al. (2007) for a review of different change-point tests). The Pettitt test is a rank-based test based on a version of the Mann-Whitney statistic to test whether two samples come from the same population. It allows detection of change-points in the mean at an unknown point in time. Since it is non-parametric (no distributional assumptions are required), it is less sensitive to the presence of outliers and to skewed distributions (as is generally the case for annual maximum peak discharge). Another advantage is that it is possible to compute the test statistical significance using the approximating limiting distribution for continuous distributions (Pettitt, 1979). Even though it is possible that multiple change-points are present, in this study we assume that there is no more than one change-point to avoid dividing the time series into several sub-series, possibly affecting our capability of performing meaningful trend analysis.

As shown in the literature (e.g., Katz and Brown, 1992; Meehl et al., 2000), change-points in variance could have a significant impact on the extremes by increasing or decreasing the scatter in the data (see Villarini et al. (2009a) for a recent discussion). Therefore, in addition to testing for the presence of abrupt changes in the mean, change-points in variance are also tested by means of the Pettitt test applied to the squared residuals (Pegram, 2000) obtained with respect to a line computed by means of local polynomial regression (loess function (Cleveland, 1979) with a span of 0.75). We selected a significance level of 5% when showing the results from the change-point analyses.

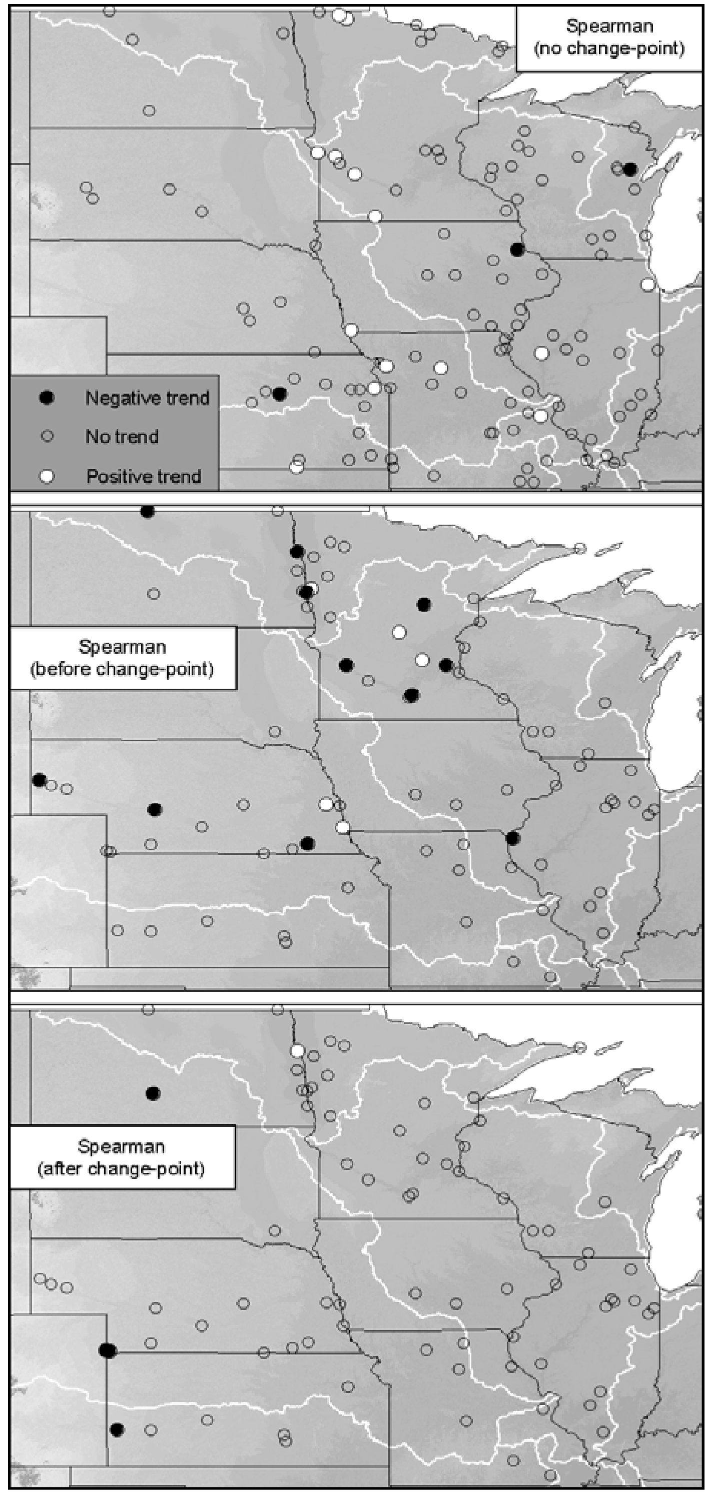

Figure 4. Maps with the results of Spearman test for the series without change-point in mean (upper panel), and with change-point in mean (middle and bottom panels). The test is significant at the 5% level.

The presence of linear trends is examined by means of two non-parametric linear trend tests, Mann-Kendall and Spearman tests (e.g., Mann, 1945; Kendall, 1975; Helsel and Hirsch, 1993; Conover, 1999; McCuen, 2002; Kundzewicz and Robson, 2004), which are commonly used in this type of analysis. Both of these tests present similar power (see Yue et al. (2002) for an extensive comparison). Using more than one test will also provide a clearer indication about the presence or absence of a trend (e.g., Zhang et al., 2004). Since these tests are widely used, for sake of brevity we do not discuss them in this paper and refer the interested reader to the literature (among others, see Helsel and Hirsch (1993) for an extensive discussion). In this study we focus on the investigation of linear trends, even though we acknowledge that trends other than linear could be present (e.g., Hall and Tajvidi, 2000; Ramesh and Davison, 2002; Villarini et al., 2009b). We selected a significance level of 5% when showing the results from the trend analyses.

Extreme Value Distribution and Scaling Analyses

In this study, for each of the m stations we have a sample of n annual maximum instantaneous flood peaks. Let us consider the random variable X_{ij}, where the subscript i refers to the i^{th} stream gage station and j to the j^{th} year. For each station that does not present statistically significant change-points in mean and variance and linear trend, we can describe its flood peak distribution in terms of its cumulative distribution function $F_i(x) = P[X_{ij} \leq x]$.

For hydrological applications, the Generalized Extreme Value (GEV) distribution has been widely used to parametrically describe the flood records (e.g., Stedinger and Lu, 1995; Hosking and Wallis, 1997; Katz et al., 2002). From a theoretical standpoint, the GEV distribution represents the limiting distribution of a series of maxima of independent (or weakly dependent) and identically distributed random variables (e.g., Leadbetter, 1983). The GEV distribution can also be described in terms of seasonal mixtures of exponentially or GEV distributed random variables (e.g., Waylen and Woo, 1982; Rossi et al., 1984; Morrison and Smith, 2002; Villarini and Smith, 2010).

The cumulative density function of the GEV distribution can be written as:

$$F_i\left(x \mid \mu_i, \sigma_i, \xi_i\right) = \exp\left\{-\left[1+\xi_i\left(\frac{z-\mu_i}{\sigma_i}\right)\right]^{-1/\xi_i}\right\} \tag{1}$$

where $\mu \in [-\infty,+\infty]$ is the location parameter, $\sigma \in (0,+\infty]$ is the scale parameter, and $\xi \in [-\infty,+\infty]$ is the shape parameter. For $\xi > 0$, the distribution is unbounded above (Frechet distribution). For $\xi < 0$ (Weibull distribution), the distribution is bounded above with an upper bound of $\mu - \sigma / \xi$. The Gumbel distribution is the special case for $\xi \rightarrow 0$ and corresponds to the case of unbounded, light upper tails.

In this study, maximum likelihood estimators of the location, scale and shape parameters (e.g., Coles, 2001) are used to estimate the parameters of the GEV distribution (among others, consult Hosking (1990), Martins and Stedinger (2000), Coles (2001), Morrison and Smith (2002) for a discussion about other estimation techniques). Analyses of the upper tail of the flood peak distribution are performed by using the ξ parameter as an index of the upper tail properties (e.g., Morrison and Smith, 2002; Resnick, 2006). We investigate the impact of summer time convective systems (peaks in the period between May and July) on the upper tail of the flood peak distribution (see Villarini and Smith (2010) for similar analyses of tropical cyclones for the eastern U.S.).

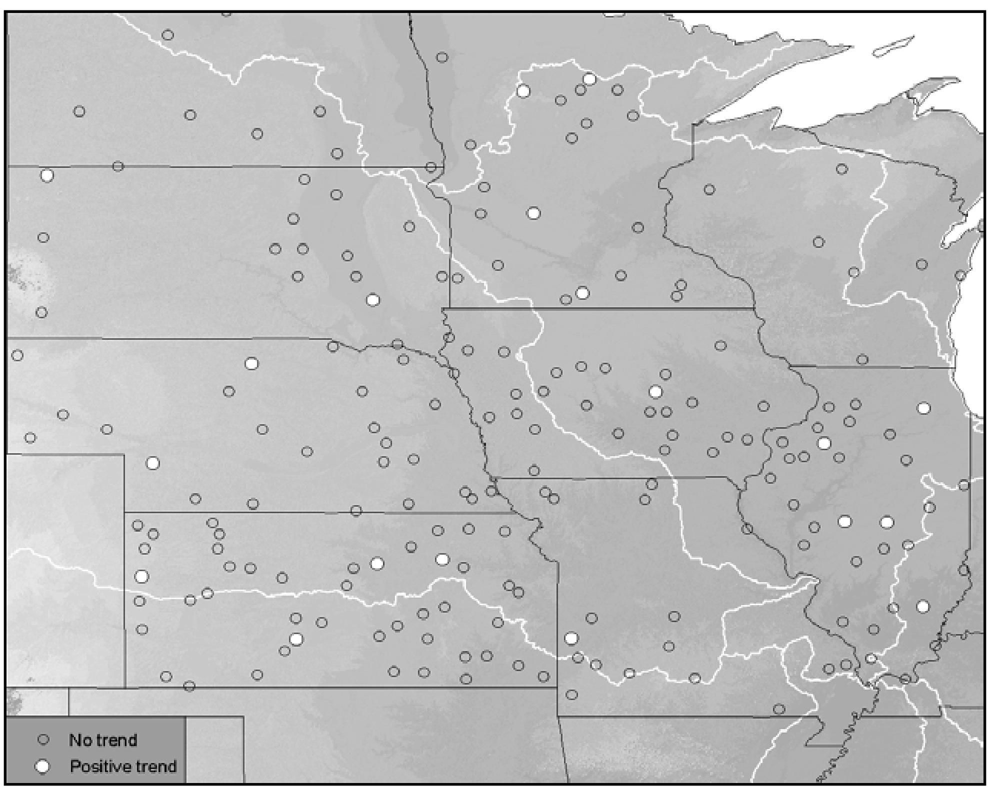

Figure 5. Map with the results of Mann-Kendall test for time series of annual maximum daily rainfall. The test is significant at the 5% level.

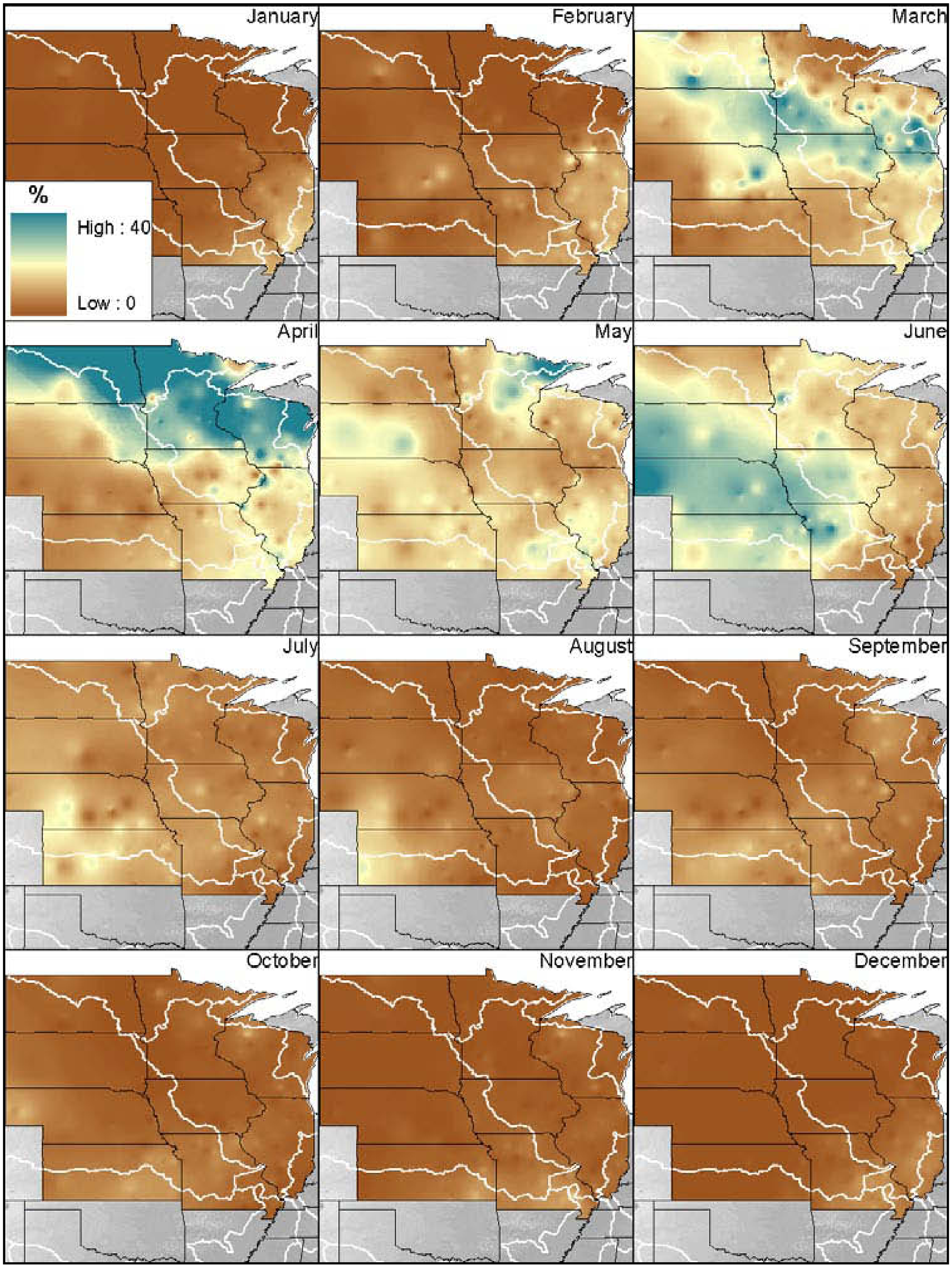

Figure 6. Maps showing the frequency of the annual maximum peak discharge for each month of the year.

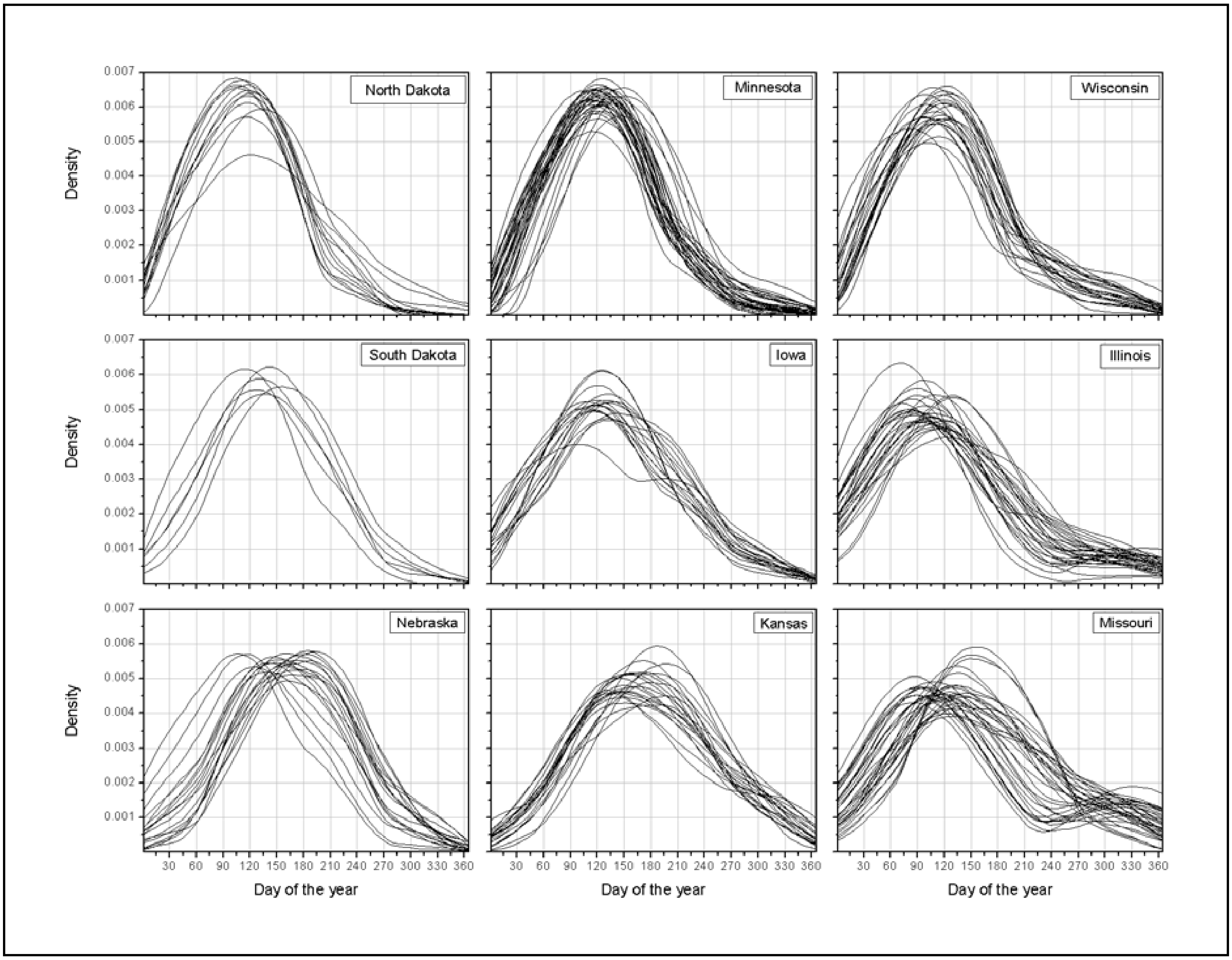

Figure 7. Plots of the seasonal distributions of annual maximum flood peaks.

Results

Stationarity

In this section, we investigate the validity of the stationarity assumption. As a preliminary analysis, we have evaluated the independence assumption by checking whether the lag-one autocorrelation value was significantly different from zero. In about 13% of the stations, we found that the lag-one correlation was statistically significant. In those cases, the violation of the independence assumption would possibly affect the significance of the linear trend tests (e.g., Kulkarni and von Stroch, 1995; Hamed and Rao, 1998; Yue and Wang, 2002). As noted by Cox and Stuart (1955), "positive serial correlation among the observations would increase the chance of significant answer even in the absence of a trend." Moreover, even if not considered in this study, the presence of long-term persistence (e.g., Hurst, 1951; Beran, 1994; Koutsoyiannis, 2006) could have an impact on the results of the linear trend analysis (e.g., Cohn and Lins, 2005; Koutsoyiannis and Montanari, 2007; Hamed, 2009). It is also possible that abrupt changes in the mean and/or variance could be responsible for this significant lag-one autocorrelation. In this study, we do not apply corrections to account for serial correlation or long-term persistence, and it is possible that some of the trends that we detect are deemed significant, even if no actual trend is present.

As mentioned above, we first test the data for change-points and then for linear trends. Change point analysis, both in mean and variance, is performed using the Pettitt test. We have summarized the results in Figure 2. Out of 196 stations, 40% of the stations exhibit a change-point in mean. Of these, 63% show an increase in mean after the change-point, 36% in variance, almost evenly distributed between increasing and decreasing variance after the change-point and 21% a change-point both in mean and variance. These change-points reflect changes in land use/land cover, agricultural practice and construction of dams (e.g., Miller and Frink, 1984; Hadley et al., 1987; Perry, 1994; Krug, 1996; Pegg et al., 2003; Schilling and Libra, 2003; Zhang and Schilling, 2006; Billington and Jackson, 2006; Schilling et al., 2008; Juckem et al., 2008; Hejazi and Markus, 2009).

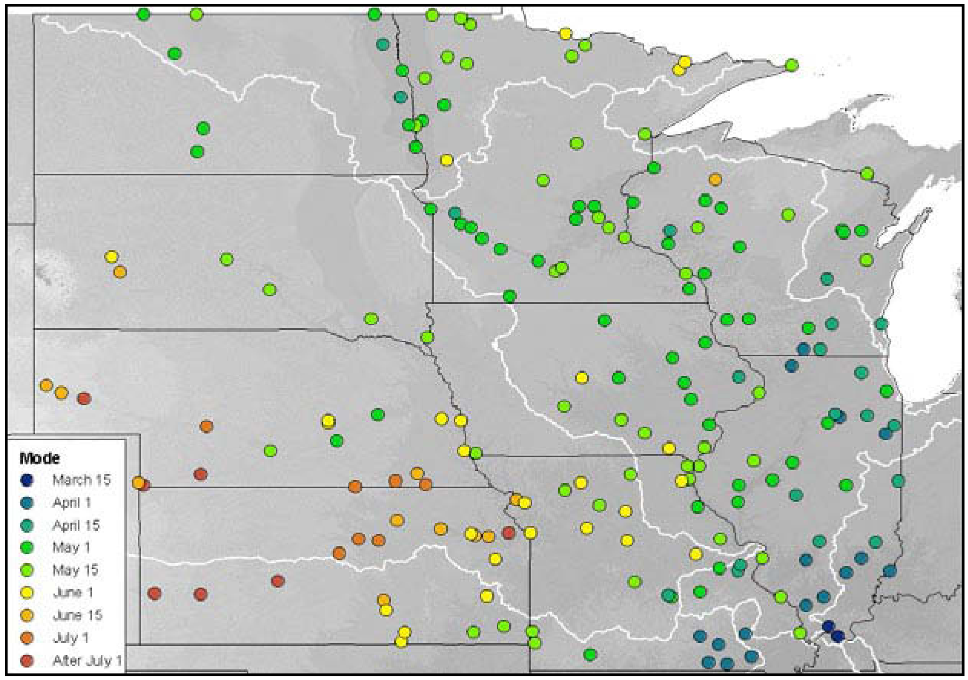

Figure 8. Map with the mode of the seasonal distribution of annual maximum flood peaks.

For the stations with a significant change-point, we examined the metadata (maintained by the USGS) associated with their records. In 25% of the cases we found that a change-point in mean and/or variance was within a range of ten years of changes reported in the metadata. In most cases, the change-point was related to qualifying code "6," which indicates "Discharge affected by Regulation or Diversion." Nonetheless, in the cases where no USGS code matched the year of the change-point, visual examination of these time series tends to support the validity of our approach.

Following the change-point analysis, we performed linear trend analysis by means of Mann-Kendall and Spearman tests. For a given record, the tests are performed on the entire time series if there is no statistically significant change-point in mean. If a change-point in mean is detected, linear trend analysis is performed on the two sub-series (before and after the change-point). We have summarized the results of the Mann-Kendall test in Figure 3 and of the Spearman test in Figure 4. In the upper panels we have the results for the tests applied on the entire time series, with no statistically significant change-point detected). In the majority of the cases no statistically significant trend is detected (both Spearman and Mann-Kendall tests lead to similar conclusions). We also note how a limited number of stations from Minnesota to Missouri tend to present a statistically significant increasing trend, suggesting that this area could be experiencing an increase in flood peak magnitude. Nonetheless, the number of stations exhibiting increasing trends is too limited to provide a clear indication of increasing trends in the region.

To evaluate whether these increasing trends could be associated with an increase in the extreme rainfall in the region, we have examined the presence of linear trends in annual maximum daily rainfall (these rain gage stations do not present a statistically significant change-point in mean or variance). For southern Wisconsin, Potter (1991), Gebert and Krug (1996) found that trends in annual rainfall were not responsible for trends in the discharge records. For northern Illinois, Changnon and Demissie (1996) and Hejazi and Markus (2009) found that increasing precipitation has a smaller impact than increasing urbanization. As shown in Figure 5 most of these rain gages do not present a statistically significant trend at the 5% level according to the Mann-Kendall test, with similar results for the Spearman test. However, we also notice that none of the stations present a decreasing trend, while 19 of them indicate a possible increasing trend in rainfall over the study area. Given the limited number of stream gage and rain gage stations presenting an increasing trend, it is difficult to conclude that increasing trends in rainfall are responsible for increasing trends in discharge (see also Small et al. (2006)).

In the middle and bottom panels of Figures 3 and 4 we have the results for the stations for which a statistically significant change-point in mean is detected. Many of the stations do not present a statistically significant trend. This is more apparent for the time series after the change-point. When considering the time series before the change-point, we note that few stations present a decreasing trend, in particular in Minnesota and the eastern side of the study domain (e.g., Rasmussen and Perry, 2001). Nonetheless, similar to what we found in our previous studies (Villarini et al., 2009a; Villarini and Smith, 2010), change-points rather than linear trends are responsible for most violations of the stationarity assumption.

Mixture Distribution

Villarini and Smith (2010) highlighted the importance of mixture distributions in describing the flood peak distributions in the eastern U.S. In particular, they showed that there was a marked spatial heterogeneity when looking at peaks

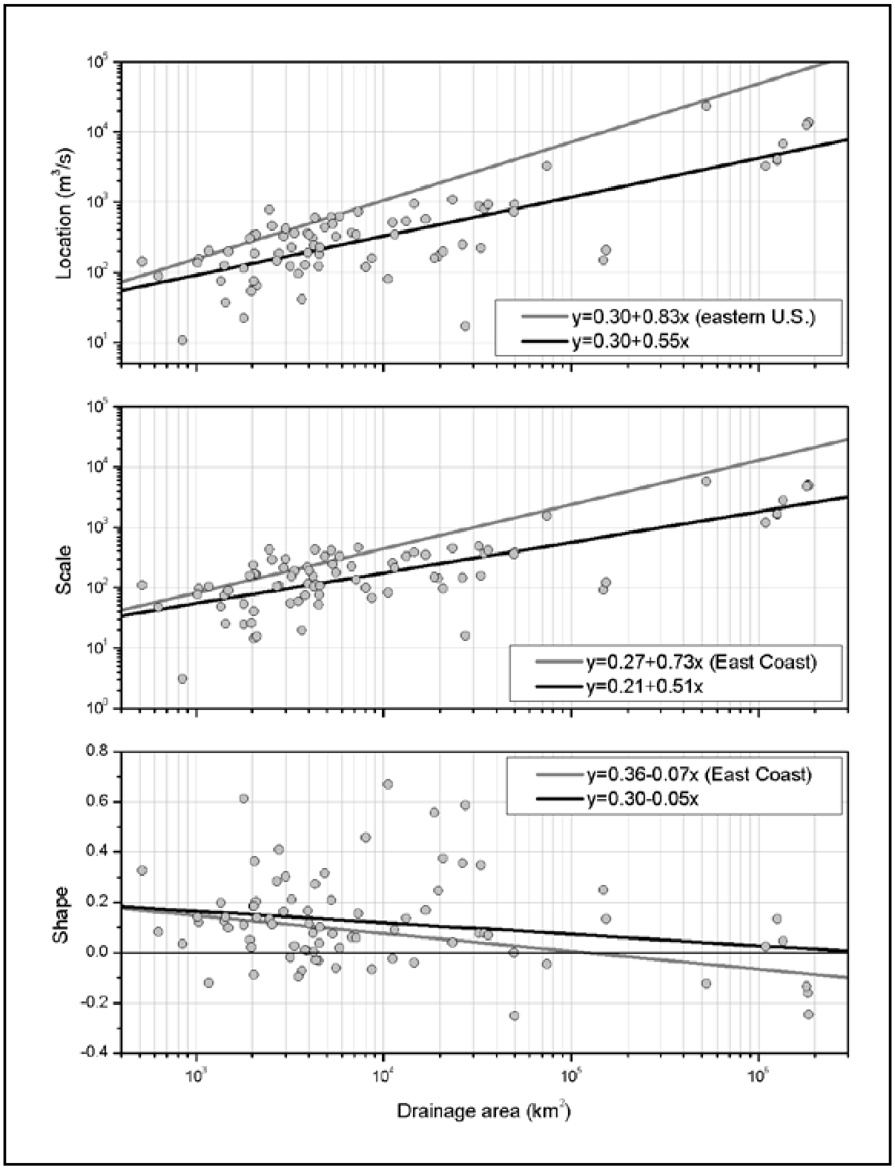

Figure 9. Plot of the parameters of the GEV distribution as a function of drainage area for the series without change-points (in mean and variance) or linear trends. The results for the eastern U.S. are based on the work by Villarini and Smith (2010).

caused by tropical cyclones, winter-spring extra tropical systems and summertime organized convective storms. In this paper we study mixture distributions by using months as proxy for different generating mechanisms (see also Diehl and Potter (1987); Knox (1988); Olsen et al. (1999); Novotny and Stefan (2007)). We have summarized our results in Figure 6. Over the study region there is large spatial heterogeneity. Most of the peaks in the south-eastern part of the domain are concentrated in the first five months of the year. Most of the peaks in the northern part of the domain (North Dakota, Minnesota, and Wisconsin) occur between March and May, likely related to snow melt, rain-on-snow and rain over frozen ground (e.g., Diehl and Potter, 1987; Knox, 1988; Hirschboeck, 1991; Olsen et al., 1999). Over the rest of the domain, most of the peaks are concentrated in the period May-July, with the majority of them during June (e.g., Diehl and Potter, 1987; Knox, 1988; McAnelly and Cotton, 1899; Hirschboeck, 1991; Silberberg, 1997; Olsen et al., 1999; Zhang et al., 2001; Changnon and Kunkel, 2006). These peaks are related to organized summertime convective systems originating from the Rocky Mountains and moving across the Midwest U.S., reaching the western ridge of the Appalachian (e.g., Silberberg, 1997). These events are also responsible for some of the most damaging floods in the area (e.g., Changnon, 1997, 1999).

We can also evaluate the monthly frequency distribution by looking at the empirical probability density function. We have summarized our results in Figure 7, where we try to maintain the geographic arrangement by plotting the most northern states in the upper panels and the most western ones in the left panels, and so on. In the vast majority of the cases, the seasonal distribution is uni-modal, although some stations in Missouri present a second mode, with the mode of the distribution that tends to occur earlier in the year in Illinois and then in the northern states, as expected from Figure 6. In Figure 8 we show the spatial distribution of the mode of the seasonal distribution. In Illinois and Southern Missouri, the peak of the distribution is before April 1st. By May 1st, the peaks of seasonal distribution have moved north-westward, likely associated with higher temperatures causing snowmelt and rain-on-snow. By June 1st, we have the highest frequency of flood peaks in the north-eastern and mid-southern parts of the study region. The modes that occur later in the year are for stations close to the Kansas-Nebraska border. These results highlight the marked heterogeneity in flood generating mechanisms over this region.

Extreme Value Distribution and Tail Properties

In this subsection we use the GEV distribution to investigate the scaling and upper tail properties of the flood peak distribution. Moreover, we investigate the impact of convective systems that occurred during the May-July period on the upper tail of the flood peak distribution. The GEV modeling is performed only on those stations that did not present statistically significant change-points in mean and variance and linear trends. There are 81 stations fulfilling this requirement.

Previous studies found that there is a relation between the GEV parameters and drainage area (e.g., Morrison and Smith, 2002; Northrop, 2004; Villarini and Smith, 2010). In particular, for the eastern U.S. Villarini and Smith (2010) found that the location and scale parameters showed a power-law behavior (linearity in the log-log domain) with an exponent of about 0.7-0.8, while the shape parameter showed a linearly decreasing behavior in the log-linear domain, with a slope of -0.07. In Figure 9 we summarize the results for the Midwest U.S. In agreement with previous studies (e.g., Morrison and Smith, 2002; Northrop, 2004; Villarini and Smith, 2010), the location and scale parameters present a power-law behavior, with an exponent of about 0.5. In the same figure we have also added the results by Villarini and Smith (2010) for the eastern U.S.. The exponent in the log-log relation for the Midwest U.S. is less steep compared to the eastern U.S., with the basins in the eastern U.S. showing larger values in both location and scale parameters for the drainage areas considered in this study. Consider for instance a basin with an area of 10000 km^2. Both of the parameters are of about an order of magnitude larger in the eastern U.S. than in the Midwest U.S., suggesting a much larger value of both flood magnitude and variability. The shape parameter tends to decrease with drainage area (slope value of -0.05), with a slope value different from zero at the 5% significance level. Compared to the eastern U.S., the shape parameters tend to be smaller for the drainage areas considered in this study. These results suggest a general tendency for these stations towards a lighter tail compared to the eastern U.S..

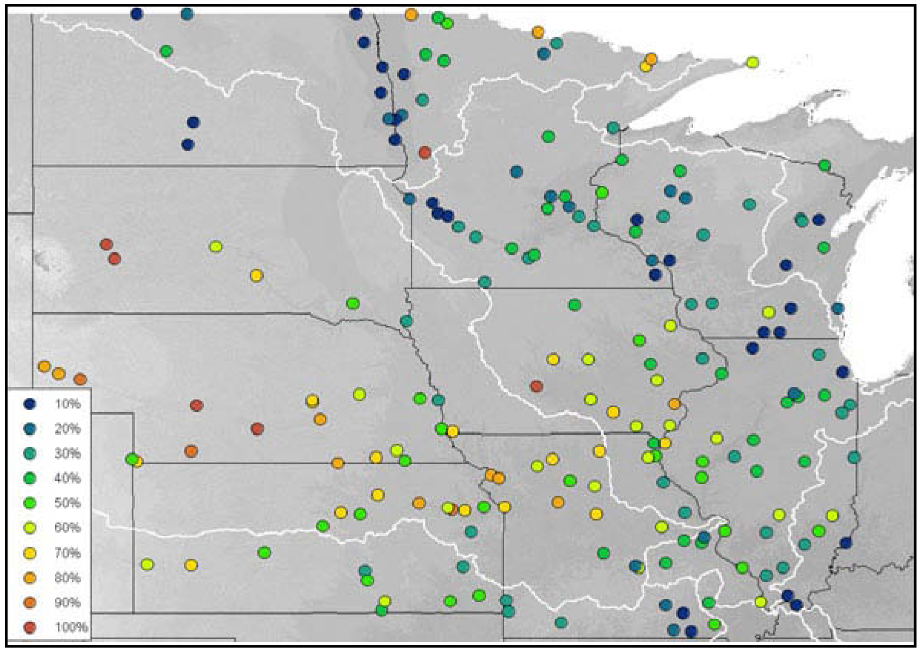

Figure 10. Map with the percentage of the ten largest flood peaks during the May-June-July period.

Organized convective systems during the May-June-July period are responsible for some of the largest peaks in the records. Another way of looking at the impact of May-June-July peaks on the upper tail of the flood peak distribution is by plotting (for all of the stations) the percentage of the ten largest peaks that occurred during this period. As shown in Figure 10, we have some of the highest values in the western part of the domain, with values larger than 50% (and up to 100%) in most of South Dakota, Nebraska, Kansas, Iowa and northern Missouri. These percentages tend to decrease as we move northward and eastward.

The impact of organized convective systems on the upper tail of the flood peak distribution is investigated by comparing the estimates of the shape parameter for the entire record against those from the records without the May, June and July peaks. As shown in Figure 11, we tend to have smaller values of the shape parameter, implying that these events play a large role in the characterization of the upper tail of the flood peak distributions for several stations in the Midwest U.S..

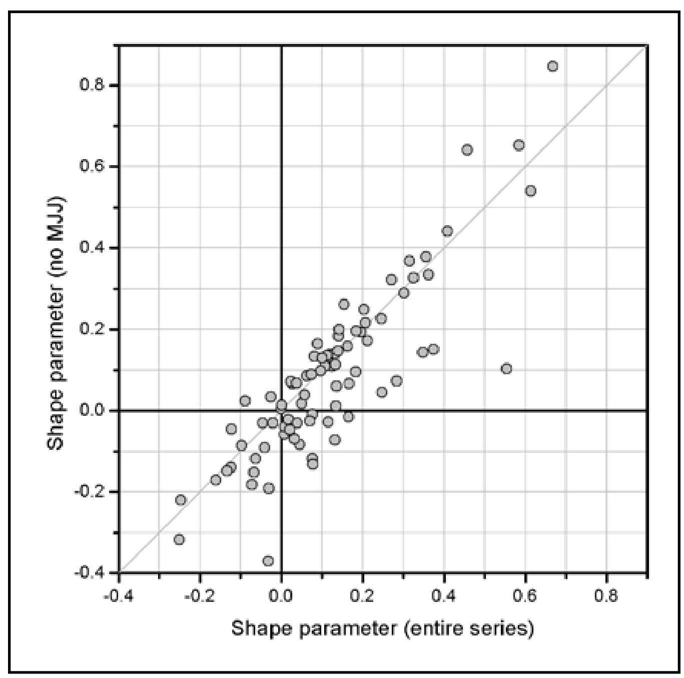

Figure 11. Plot of the shape parameters from the entire series versus the series after removing the peaks during the May-June-July period.

In Figure 12 (upper panel) we plot the spatial distribution of the shape parameter. Overall, we observe a large spatial heterogeneity, with lighter tails towards the eastern part of the study region, from eastern Minnesota down to Illinois. As we move westward, the tails tend to become heavier, in particular towards the north-western part of the domain (North and South Dakota). In the bottom panel of Figure 12 we show the differences between the shape parameter estimated from the entire record and after removing the peaks in the May-June-July period. Overall, we have positive values (lighter tails after removing the May-June-July peaks) in most of the central part of the domain, in particular in Iowa, Nebraska and Kansas, in agreement with the results of the seasonality of the flood peaks (Figures 6-8).

Conclusions

In this study we have analyzed the annual maximum instantaneous flood peak distributions for 196 USGS streamflow stations with a record of at least 75 years over the Midwest U.S. Our findings can be summarized as follows:

1. Flood peak distributions can be represented in terms of "mixtures" of different generating mechanisms. Over the study domain there was a marked seasonality, with significant spatial heterogeneities associated with spring and summer events. Organized convective systems that occur from May to July are of particular importance in determining the flood peak distribution. They are responsible for some of the largest flood peaks in most of the western part of the domain and Iowa. Events associated with snow melt and rain on frozen ground are more significant in the northern part of the domain.

2. In the vast majority of the cases, violations of the stationarity assumption are associated with change-points (both in mean and variance) rather than linear trends. These nonstationarities are often associated with anthropogenic effects, such as changes in land use and land cover, changes in agricultural practice and construction of dams and reservoirs. We cannot, however, rule out that some of the observed changes can be due to abrupt changes in the rainfall regime in the area (e.g., Lettenmaier et al., 1994; Angel and Huff, 1997; Karl and Knight, 1998; Kunkel et al., 1999; Mauget, 2003a,b). Future studies should provide a more detailed analysis of the rainfall record.

3. Only a limited number of stations presented a statistically significant trend. Based on these results and in agreement with previous studies (Olsen et al., 1999; Villarini et al., 2009a), there is little indication that anthropogenic climate change has significantly affected the flood frequency distribution for the Midwest U.S.

4. Spatial heterogeneities in flood peak distributions, upper tail properties of flood peaks and scaling properties of the flood frequency distributions were examined through analyses based on fitted GEV distributions for the stationary flood series. The location and scale parameters exhibited an increasing linear trend (in the log-log domain) as a function of drainage area, while the shape parameter showed a decreasing behavior. Heavier tails of flood peak distribution were found in the western and central parts of the study area. The eastern region showed lighter tails.

5. Flood peaks associated with summertime convective systems significantly affect the upper tail of the flood peak distribution in most of Nebraska, Kansas and Iowa. Comparison of the shape parameters estimated from the entire record and after removing peaks in the May-July period showed how the tails from the entire record were heavier than those estimated removing May-July peaks. Therefore, it is possible that the observed heavy tails could be described in terms of "mixtures" of different generating mechanisms.

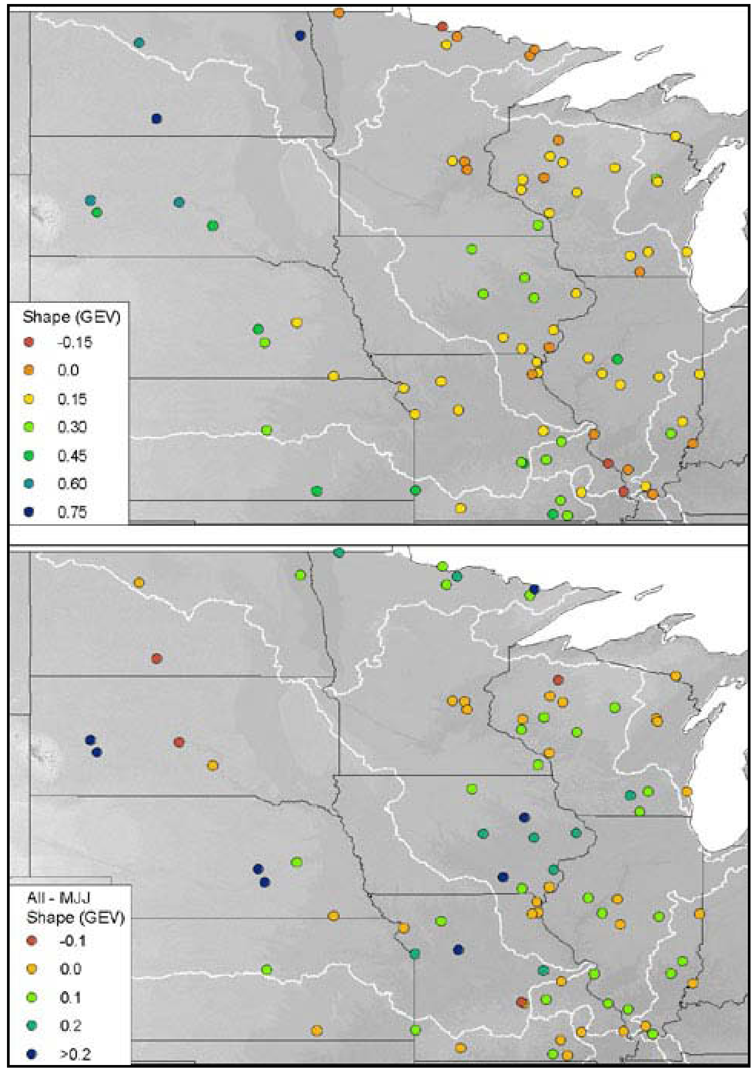

Figure 12. Map of the shape parameters of the GEV distribution for the series without change-points (in mean and variance) or linear trends (upper panel) and map with the differences in the shape parameter between the entire record and the record after removing peaks during the May-June-July period.

Acknowledgments

This research was funded by the Willis Research Network, NASA NNX07AD65G, NOAA Cooperative Institute for Climate Sciences NA08OAR4320752, NSF Biocomplexity EF-0709538, and the NSF SGER EAR-0847347.

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Biography

Gabriele Villarini is a post-doctoral research associate in the Department of Civil and Environmental Engineering at Princeton University, working with Prof. James Smith. He received his M.S. in Civil Engineering from the University of Rome "La Sapienza," and his Ph.D. in Civil and Environmental Engineering in 2008 from the University of Iowa. In 2006 he was awarded the NASA "Earth System Science Fellowship", in 2007 the "Outstanding Student Paper Award" by the Hydrology Section of the American Geophysical Union (AGU), and he is currently a Willis Research Network fellow. He has published over 20 peer-reviewed papers.

His research interests revolve around flood hydrology, extreme events, remote sensing of rainfall, and statistical modeling. In particular, he is interested in examining the impact of anthropogenic climate change on extreme flooding, rainfall, and tropical storm frequency.

Statistical Methods and Frequency Analysis

Getting From Here to Where?

Jery R. Stedinger and Veronica W. Griffis, Cornell University

Abstract

Flood risk computations by U.S. federal agencies follow guidelines in Bulletin 17, for which the latest update was published in 1982 (IACWD, 1982). It is time to update that remarkable document to address problems listed in the document by employing recent advances that address those problems, and to take advantage of the current national interest in flood risk (Stedinger and Griffis, 2008). The major focus of this paper is the challenge posed by climate change and climate variability. Extensions of the log-Pearson Type 3 model of flood risk to include changes in flood risk over time is relatively easy mathematically. The use of ENSO to anticipate changes in flood risk from year-to-year in the United States illustrates the use of this mathematical representation of the impact of climate variability on flood risk. Efforts to project the trend in the Mississippi River flood series beg the question as to whether an observed trend will continue unabated, has reached it maximum, or is really nothing other than climate variability so that the risk in expectation will soon return to its long-term average. Is stationarity dead? Overall, we do not know the present flood risk at a site because of limited records. If we allow for historical climate variability and climate change, we know even less. The issue is not whether stationarity is dead—the issue is how to use all the information we have to forecast flood risk in the future. "Where do we go from here?"

Introduction

This workshop is concerned with flood risk computations in the United States and is sponsored by several U.S. federal agencies. Currently, flood risk computations by U.S. federal agencies need to follow guidelines in Bulletin 17 (IACWD, 1982). The first section of this paper considers the evolution of those guidelines and changes currently under consideration. Stedinger and Griffis (2008) have argued that it is now time to update that remarkable document to address problems listed in the document and to make use of recent advances in flood frequency analysis that address those problems. Once those changes have been adopted, federal agencies can move on to consideration of how the Bulletin should be modified to address climate variability and climate change.

Actual and potential climate change and climate variability will increasingly challenge hydrologists, civil engineers, and planners concerned with flood risk. The 1999 National Research Council report, Improving the American River Flood Frequency Analysis, addressed the apparent increase in flood risk for the City of Sacramento in the last century (NRC, 1999). The study illustrates the dilemmas posed by possible climate change.

The Bulletin 17B log-Pearson Type 3 model of flood risk can be extended to include changes in flood risk over time. The use of ENSO to anticipate changes in flood risk from year-to-year in the United States illustrates the use of a climate index in that framework to describe variations in flood risk over time. Efforts to project the trend in the Mississippi River flood provide a more general illustration of such extensions, and the conceptual problems that arise.

Claims that stationarity is dead have caused much debate. Stationarity is the statistical framework we use to understand the variability in historical records, even if we cannot use it to carry us into the future. The challenge now is to build a statistical framework that starts with those historical records and allows us to project flood risk into the future.

Bulletin 17B and Current Federal Guidelines

In the U.S., the computation of flood risk for planning by Federal agencies is done following guidelines in Bulletin 17, for which the latest update, Bulletin 17B, was published in 1982 (IACWD, 1982). Bulletin 17B recommends using the method-of-moments (MOM) to fit a Pearson Type 3 (P3) distribution to the logarithms of the flood series, thereby yielding a log-Pearson Type 3 (LP3) distribution to model flood data. Estimates of the mean, standard deviation, and skew coefficient of the logarithms of the sample data are computed using traditional moment estimators (Stedinger et al., 1993). However, the data available at a site are generally limited to less than 100 years, and is often less than 30 years. Bulletin 17B wisely suggests the at-site skew be weighted with a regional skewness estimator, where the recommended weights are inversely proportional to the precision of each estimator, based upon a skew map first developed by Hardison (1974). Thomas (1985) and Griffis and Stedinger (2007) provide a review of the evolution of this document and the methods employed to address a range of special cases, including zero flows, outliers and historical information.

Stedinger and Griffis (2008) observe that "Bulletin 17B has served the nation for over 30 years; it is a remarkable document that has withstood the test of time and use. However, given long-standing problems listed in the document, recent advances that address those problems, and the current national interest in flood risk, the time has arrived to update Bulletin 17B in order to maintain the statistical credibility of the guidelines and to provide accurate risk and uncertainty assessments." Of particular concern are the appropriate representation and use of historical and interval data which can be done with more efficient statistical procedures (Cohn et al., 1977; Griffis et al., 2004), computation of regional skew and its actual precision (Reis et al. 2005; Gruber et al. 2008), and honest uncertainty assessments and confidence intervals for quantiles (Cohn et al. 2001). Several recent studies, including Gotvald et al. (2009), have found that regional skew can be much more informative than is indicated by the Bulletin 17B skew map (see also Tasker and Stedinger, 1985). England and Cohn (2007) summarize federal concerns.

1999 NRC American River Report

Actual and potential climate change and climate variability will increasingly challenge hydrologists, civil engineers, and planners concerned with flood risk. The 1999 National Research Council report, Improving the American River Flood Frequency Analysis, addressed the apparent increase in flood risk for the City of Sacramento in the last century (NRC, 1999; see also NRC, 1995). The problem was that all of the floods over 100,000 cfs, five in total, occurred after 1950, as shown in Figure 1. While many explanations were possible, the 1999 NRC committee concluded:

- … there is little doubt that the observed frequency of large floods on the American River is much greater in the period from 1950 to the present than it was in the period from 1905 to 1950.
- Based on the present understanding of climate dynamics [and they considered many possibilities], it is not possible to assess the relative contribution of natural and anthropogenic factors to this observed increase.
- More importantly, it is not possible to predict its likely persistence in time. The committee is very uncomfortable …"Uncomfortable" is likely to be a hallmark of future flood studies when climate change is a concern.

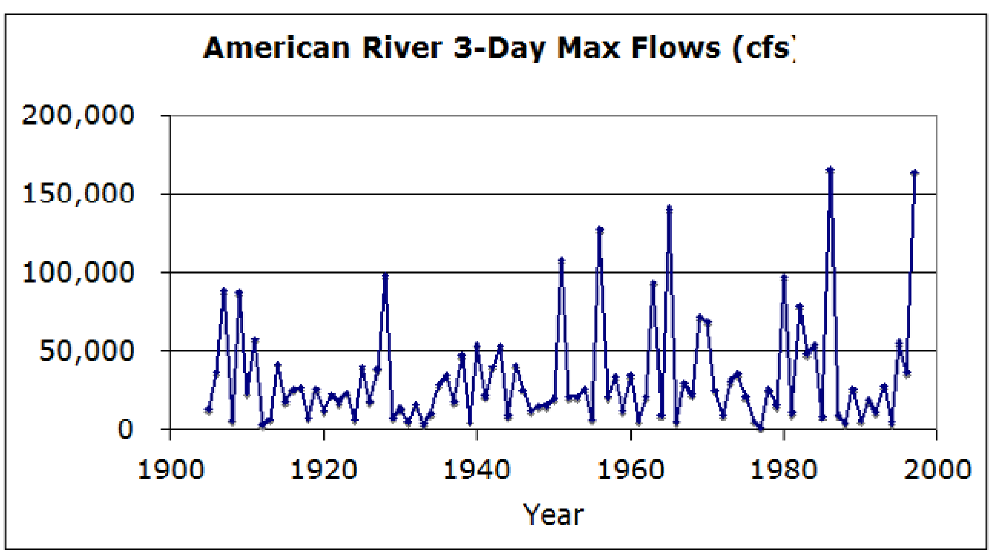

Figure 1. American River Flood Record at Fair Oaks illustrating possible change in flood risk.

Is Stationarity Dead?

The Science paper by Milly, Betancourt, Falkenmark, Hirsch, Kundzewicz, Lettenmaier, and Stouffer (2008), entitled "Stationarity is Dead: Whither Water Management" raises important issues and has been the subject of much discussion. It has been used to support a number of outlandish statements about the limited value of historical data. The report actually says: "In view of the magnitude and ubiquity of the hydroclimatic change apparently now under way, however, we assert that stationarity is dead and should no longer serve as a central, default assumption in water-resource risk assessment and planning. Finding a suitable successor is crucial for human adaptation to changing climate."

Consider the actual situation. Does climate change mean we are not interested in historical records? Of course not. Historical data tell us what flood series look like and where we start. Then we need to estimate the change, which describes where we go from there.

Dr. Beth Faber's presentation entitled, "Current Methods for Hydrologic Frequency Analysis", (Faber, 2010) and papers such as Cohn et al., (1997), Cohn et al. (2001), Reis and Stedinger (2005), and Griffis et al. (2005) document the uncertainty in log-Pearson quantile and parameter estimators with common record lengths of 100 years are less. Estimates of the 50-year, 100-year or 200-year flood with 35 - 100 years of data are highly uncertain. Cohn and Lins (2005) point out that if we incorporate long-term persistence into our analysis, we know even less. Spatial correlation decreases the value of regional information (Stedinger and Tasker, 1985; Gruber et al., 2008). So in terms of the evolution of flood risk, we do not know where we are now. And then, when faced with concerns related to climate variability and climate change, we need to ask: "How do we determine where we go from here?"

Extensions of Bulletin 17B and Climate Change: Extensions of the log-Pearson Type 3 model of flood risk to include changes in flood risk over time is relatively easy mathematically. A simple mathematical structure can address anticipated changes in overall scale (described by the log-space mean), or the shape of the distribution (described by the log-space standard deviation and skew).

Bulletin 17B can be modified to account for variability over time in flood risk by employing time-dependent parameters. Consider three models for logs of flood peaks, X = log [Q]:

1. $X_t \sim P3[\ \mu(t), \sigma, \gamma\ ]$
2. $X_t \sim P3[\ \mu(t), \sigma(t), \gamma\ ]$
3. $X_t \sim P3[\ \mu(t), \sigma(t), \gamma(t)\ ]$

where P3 stands for a Pearson Type 3 distribution with three parameters.

In the first case only the scale of the flood distribution described by $\mu(t)$ depends on time. This is quite reasonable if it is primarily the moisture content of storms, and perhaps their intensity that changes with time. Here the mean and standard deviation of the floods themselves Q both scale with $\exp[\mu(t)]$. In the second case, both the scale and the shape parameter $\sigma(t)$ depend on time. This might be appropriate if climate change was also associated with a regional shift in the causes or character of storms, such as winter rain or summer thunderstorms versus snowmelt. Finally, in the third case the second shape parameter of the LP3 distribution, the log-space skew γ also depends upon time. In the stationary case, it is often difficult to resolve the skew very well, and thus it would be that much more difficult to resolve and forecast changes in the skewness coefficient when climate variations were a concern. Both of the examples below used model 1.

Use of Climate Indices:

In terms of climate variability, the variation in these parameters might be tied to climate indices such as PDO, NAO, and ENSO. Thus, one would employ a physical observable characteristic of the climate system to explain variations in flood risk; that would be very defensible. Over the long run, effects of short-term climatic cycles (i.e. ENSO) are averaged into Bulletin 17B flood risk estimates. Kashelikar and Griffis (2008) illustrate, as have Kiem et al. (2003) and others, how an ENSO phase and intensity information can be used to adjust flood risk from year-to-year. Kashelikar and Griffis used model 1 above, wherein their mean $\mu(t)$ was a linear function of the forecasted value of 3-month SST anomaly. They illustrate generation of year-specific flood risk distributions that can be used to improved reservoir operation and management.

Flood Risk and the Mississippi River

Stedinger and Crainiceanu (2001, 2002) used a record for the 1898-1998 period constructed for the Upper Mississippi Basin by the U.S. Army Corps of Engineers for their ongoing frequency studies to illustrate the challenge of forecasting possible climate change (Goldman, 2000). This data set has several changes from that employed by Olsen et al. (1999) and Matalas and Olson (2001). As with the Olsen analysis, trends were significant in this revised data set using a simple test based on linear regression. Such tests have their limitations (Cohn and Lins, 2005). The trend at Hannibal, MO was statistically significant at the 0.01 level using a two-tailed test. This demonstrates that the assumption of independent identically distributed flood peaks can be rejected.

To study the impact of different representations of climate variability on flood-risk assessment and project design they considered three reasonable models:

a. The i.i.d. Log-Normal Model. This model assumes that the maximum annual floods Q_t are independent, identically distributed random variables where $\log(Q_t) \sim N(\mu, \sigma^2)$. This is a traditional model used for flood-risk management. The federal guidelines generally recommend a log-Pearson Type 3 distribution [IACWD 1982], which for a log-space skew of zero simplifies to a log-normal distribution, which was found to be adequate in this instance.

b. The Log-Normal Trend Model. This model assumes that the maximum annual floods have a lognormal distribution around a linear trend, so that

$$\log(Q_t) = \mu + \lambda * (t - \bar{t}) + \varepsilon_t$$

where ε_t are i.i.d. $N(0, \sigma^2)$Here $\bar{t} = (T+1)/2$ wherein T is the record length.

c. Log-Normal ARMA Model. This model assumes that the maximum annual floods Q_t are generated by a stationary low-order Autoregressive Moving-Average (ARMA) process (p, q) for the log-flood series [Box et al. 1994]:

$$\log(Q_t) - \mu \sim ARMA(p, q)$$

This model explains the observed upward trend as extra variability due to persistence in a stationary time series. This modeling approach is particularly interesting because it preserves the assumption of stationary variability.

Table 1 reports the estimated values of the parameters for the models for the Mississippi at Hannibal. The parameter μ is the overall mean for the stationary models (LN-i.i.d. and LN-ARMA) and the location parameter for the non-stationary model (LN-Trend). Here the parameter φ of the LN-ARMA(2,1) model is the biggest absolute value of the roots of the AR(2) polynomial from the ARMA(2,1) structure. This parameter is the rate at which a forecast returns to the unconditional mean of the process. Finally, σ is the standard deviation for all 3 models.

LN-i.i.d.	μ =12.2534		σ =0.3619
LN-Trend	μ =12.2534	λ =0.0047	σ =0.3388
LN-ARMA (2,1)*	μ =12.2534	ϕ =0.8701	σ =0.3619

Table 1. Log-space model parameter estimates for Hannibal.
** For the ARMA model φ_1 =1.008, φ_2 =-0.12, θ =0.77.*

All three risk models considered above can generate forecasts of the distribution of floods in the future as described in Table 2. C stands for trend continues over the planning period, and S for trend stops at the 1998 level and the subsequent risk remains constant at that level.

Models			
i.i.d. Log Normal	**Trend Log Normal**		**ARMA Log Normal**
Constant unconditional flood-risk distribution	C: Project continued trend with constant variance	S: Projected risk stops at the 1998 level	Conditional mean and variance based upon 1898-1998 record

Table 2. Flood-risk forecasts considered.

Consider now what those forecasts would actually look like for the flood records at Hannibal. Figure 2 shows the original flood series from 1898 to 1998 and its mean, as well as the linear variation in the mean represented by the LN-Trend model and its projection over the 1999-2030 period. Also included is the LN-ARMA one-step-ahead conditional mean $\mu + \delta_t$ for the flood series given what has come before, and the LN-ARMA conditional mean for the 1999-2030 period given what had occurred up until 1998. As can be seen, the LN-ARMA-model conditional mean forecast decays to the long-term mean after a decade or so.

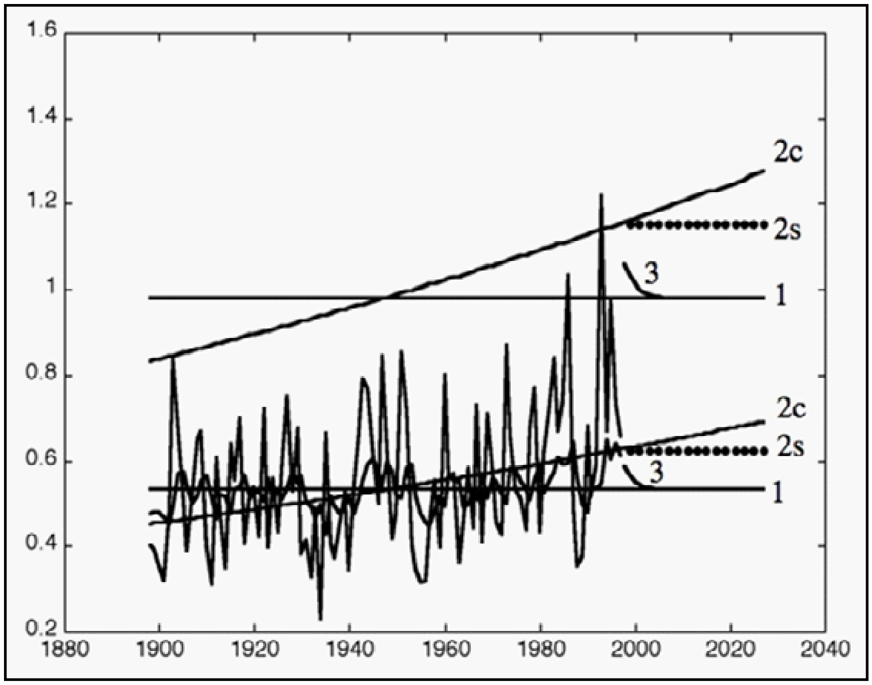

Figure 2. Mean and 50-year flood levels over historical record and planning period, for Hannibal record using three flood risk models. (1) LN-iid; (2) LN-Trend, continues [C] or stops [S]; (3) LN-ARMA(2,1) one-step ahead forecast over historical period and forecast for beyond historical record (flood flows in million cfs).

Figure 2 illustrates the variation in the risk of large floods implicit in the LN-i.i.d. and LN-Trend risk models. Displayed in the figure for each of those two models are the thresholds with an exceedance probability of 2% for each year. For the LN-i.i.d. model this threshold is a straight horizontal line that was almost exceeded in 1972, and was exceeded by the 1993 event. For the LN-Trend model the 2% exceedance threshold is a straight line with a positive slope. The projection of flood risk over the 1999-2030 period with the LN-Trend model is either a continuation of that trend or a constant risk at the 1998 level. Both of these projections of the mean and the 2% exceedance probability threshold are shown in the figure. Finally the figure shows the projection of the 2% exceedance probability threshold for the ARMA (2, 1) model. As with the ARMA projection of the mean, the forecast of the 2% exceedance threshold decays to the long-run value after a decade or so.

In this example, variation in flood risk is likely to affect flood-risk management if decision parameters can be adjusted on a year-to-year basis. However, variations in flood risk are likely to have disappeared before major construction projects can be designed, authorized and completed. What is not clear is how to project a real climate change if we do not understand the physical mechanisms causing that change.

This example shows that stationary time-series models are very flexible and produce a reasonable interpretation of historical records that can be used to project flood risk. In this framework, apparent trends in a flood record can be interpreted as the observed parts of a cycle in the natural variation in flood risk. Unfortunately alternative assumptions and models can lead to very different flood risk forecasts, and it is hard to determine which one is appropriate. It is particularly difficult to distinguish a modest trend from long-term persistence (Cohn and Lins, 2005), which is also likely to be present (NRC, 1998).

Conclusion

The NRC study Decade-to-Century-Scale Climate Variability and Change (NRC, 1998): concludes: "The evidence of natural variation in the climate system - which was once assumed to be relatively stable - clearly reveals that climate has changed, is changing, and will continue to do so with or without anthropogenic influences. Furthermore, compounding the inevitable hazard of natural climate variations is the potential for long-term anthropogenic climate alteration."

So is Stationarity dead? Stationarity remains in most cases as our paradigm for analyzing historical records. It is still the default for any analysis. We need to demonstrate that in fact, real climate is affecting the character of the hydrologic series of interest to us. Stationarity will most likely be the paradigm for analyzing persistence and variability in hydroclimatic records, to which we need to add projected anthropogenic change (which is then a nonstationarity, as was urbanization and development factors in the past).

Extensions of the log-Pearson Type 3 model of flood risk to include changes in flood risk over time is relatively easy from a mathematical standpoint. A simple mathematical structure can address anticipated changes in overall scale (described by the log-space mean), or the shape of the distribution (described by the log-space standard deviation and skew). The use of ENSO to anticipate changes in flood risk from year-to-year in the United States illustrates the use of this mathematical representation of the impact of climate variability on flood risk. However, projecting flood risk into the future is more problematic. Efforts to project the trend in the Mississippi River flood series beg the question as to whether an observed trend will continue unabated, has reached it maximum, or is really nothing other than climate variability so that the risk in expectation will soon return to its long-term average.

Overall, we do not know the present flood risk at a site because of limited records for a site, and the imprecision of regional relationships, assuming annual floods are independent over time. If we allow for historical climate variability, we know even less. In water-supply management we often use period-of-record planning, which hides uncertainty. Now with climate change, we need to project from the uncertainty of our current knowledge based upon the past record to estimate the risk in the future. Formulating models is easy, but are those models credible? A model adding a trend in scale (log-space mean) is attractive and simple. Uncertainty can be added, but would such an addition be accepted? To be defensible we should base flood-risk forecasts upon some change in climate-characteristics for which we have a physical-causal basis for multi-decadal projections. And even if climate has been stationary, for at least a century man has been changing and will continue to change the landscape and hydrologic systems across the United States. Change in flood risk is not new.

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Biography

Jery Stedinger attended the University of California at Berkeley and Harvard University. He spent sabbaticals at the U.S. Geological Survey's and the US Army Corps of Engineers Institute for Water Resources, and their Hydrologic Engineering Center (HEC) in Davis. Dr. Stedinger's research has focused on statistical and risk issues in hydrology and the optimal operation of water resource systems. Research projects have addressed flood frequency analysis including the use of historical and paleoflood data, regional hydrologic regression analyses, risk and uncertainty analysis of flood-risk reduction projects, watershed modeling, dam safety, water resource system simulation, and efficient multiple-reservoir and hydropower system operation and system design. Jery was the 1997 winner of the ASCE Julian Hinds Award. In 2004 he received the Prince Sultan Bin Abdulaziz International Prize for Water for the Surface Water Branch for his work on flood risk management.

Hydrologic Frequency Analysis in a Changing Climate

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Abstract

The assumptions of traditional flood frequency analysis that annual maximum floods at a given location are independent and identically distributed (i.e., the notion that floods are stationary) has been challenged in light of the impacts of observed climate variability and change as well as changes induced by land use modifications. This has profound implications for yearly flood and drought management efforts and for longer term facilities design and management. Yearly flood and drought management efforts are based on historic stationary risk but, the risk varies significantly from year to year – for example, during El Nino years the North Western US has a very low probability of high flows and consequently a diminished flood risk relative to the historic stationary risk. Clearly, the ability to skillfully quantify the time varying risk is extremely important for efficient and optimal planning of resources. Similarly, insights into the variability of hydrologic frequency and consequently the risks are key to devising sustainable planning and management strategies for water and other resources.

In this paper we offer two approaches for nonstationary hydrologic frequency analysis – (i) local polynomial likelihood method and (ii) Generalized Extreme Value (GEV) with covariates. In the local polynomial method, the frequency analysis is cast as a conditional probability density function (PDF) estimation problem – where in the PDF of the flood variable (e.g., annual maximum) Q_t is estimated conditioned on a suite of covariates or independent variables such as climate information, X_t. The estimation is performed 'locally' within a neighborhood of X_t, thus, providing the ability to capture any arbitrary features present in the data. The covariates are based on the knowledge of the large scale climate system that modulates the regional hydrologic frequency. In the GEV method the scale parameter is assumed to vary with time and dependent on covariates, such as X_t – a regression model is fit to capture this relationship. Thus, for each year conditioned on the covariate the scale parameter of the GEV is estimated and consequently the appropriate quantile and risk estimates. To model under climate change the regression for the scale parameter is developed using observational data and the climate change projections can then be used to obtain the scale parameters for the future. We demonstrate these two approaches with application to nonstationary flood quantile estimation at interannual and decadal time scales under changing climate. Extensions to regional hydrologic frequency estimation are also discussed.

Introduction

Hydrologic frequency analysis entails estimating the desired quantiles of extreme hydrologic events such as floods, droughts, etc. Typically, the quantiles of interest are p=0.01, p=0.002, which correspond to events with a return period of 100-year or 500-years, and are useful for infrastructure design and also for resource planning and management of resources for each year and over a period. In practice these estimates have to be obtained from a small number of observations (~50 to 100 years long). Traditional methods for frequency analysis assume that the data are independent and identically distributed (*iid*) and are drawn from a single population with a known Probability Density Function (PDF) – i.e., assuming 'stationarity' of the distribution. An appropriate PDF is selected from a candidate set of PDFs, and distributions that are commonly used and prescribed by regulatory agencies include the Log Pearson type III (LP3), Log Normal (LN) and Extreme Value type I (EVI) distributions (see Kite, 1977; IACWD, 1982; Chow et al., 1988). There are statistical tests to discriminate between choices of distributions including L-moments methods (see Kite, 1977; Vogel 1986; Hosking, 1990; Vogel and McMartin, 1991). Generalized Extreme Value (GEV) distributions offer a generalized approach to modeling a variety of tail behavior – as the quantiles desired are in the tails of the distribution. This has been widely used in describing flood characteristics (Lettenmaier et al., 1987; Hosking and Wallis, 1988; Stedinger and Lu, 1995; Morrison and Smith, 2002). However, it is often difficult to distinguish between candidate models for a given data set, and best fit criteria emphasize the bulk of the distribution rather than its tails. Consequently, there is considerable uncertainty as to the best underlying model for the estimation of the quantiles. Nonparametric methods do not assume a distributional form of the data and are data driven – in that they estimate the quantiles by smoothing the empirical quantile function or by using kernel density estimators (for details see, Lall et al., 1993; Moon et al., 1993 and, Moon and Lall, 1994). Recently Apipattanavis et al. (2010) developed a local polynomial based flood frequency estimator that offers an attractive alternative to kernel based methods, which efficiently smoothes the empirical quantile function; they demonstrated the utility of this for frequency estimation in data from mixed population. However, within this rich literature on flood frequency estimation, 'stationarity' is assumed of the hydrologic process and thus the data is fit to a 'single' model, resulting in stationary quantile estimates.

There is growing evidence of 'nonstationarity' of hydrologic frequency of floods and droughts. The nonstationarity is recognized to be originating from the underlying state of the large-scale climate modulated by structured low frequency climate functions (Lins and Slack, 1999; Baldwind and Lall, 1999; Jain and Lall, 2000; Pizaro and Lall, 2002; Franks and Kuczera, 2002). A variation in the base climate state as defined by Sea Surface Temperatures or Atmospheric Circulation Indices can markedly change patterns of atmospheric moisture transport in the flood season, consequently changing the probability distribution of floods in a given year at a particular location. It is now widely acknowledged that well organized low-frequency climate modes, such as interannual El Niño Southern Oscillation (ENSO) and interdecadal Pacific Decadal Oscillation (PDO) modulate regional climates on annual and interannual timescales around the globe (Wenland and Bryson, 1981; Hirschboeck, 1991). The ENSO is a tropical Pacific ocean coupled ocean-atmosphere phenomena, while the PDO is the indicator of dominant of oceanic variability in the Northern Pacific. Several studies have shown that major extremes of floods and droughts, especially in the Western US, are associated with the state of ENSO and PDO (Trenberth and Guillemot, 1996; Piechota and Dracup, 1996; Jain and Lall, 2000; Pizzaro and Lall, 2002).

The National Research Council (NRC) study on the American river provides an excellent case study of nonstationarity (NRC, 1995; NRC, 1999). Flood protection structures on this river were designed based on stationary flood frequency estimation approach in the mid-20th century. Subsequently, in the latter part of the century the pre-infrastructure maximum flood was exceeded at least 5 times – thus, severely reducing the flood protection to the community. The increase in wet events was linked to large-scale climate states in these two NRC studies. Therefore, it is clear that large-scale climate forcings should be used to estimate hydrologic frequency so that the infrastructure can be designed and managed robustly.

To effectively model the nonstationarity in the hydrologic frequency, traditional frequency methods described above have to be modified to incorporate the large-scale forcings. In other words, the quantiles have to be estimated 'conditional' on the state of the forcings. Quantile regression (Koenker and Bassett, 1978; Yu et al., 2003) has been a traditional approach to conditional quantile estimation. In this, each desired quantile is estimated by fitting a regression to a set of conditioning (or predictor or covariate) variables. This is computationally intensive and suffers from the drawback that the quantile estimates are not guaranteed to be ordered – i.e., the p=0.95 quantile is not guaranteed to be higher than p=0.9 quantile as they are estimated independently. Davison and Ramesh (2000) developed a local likelihood approach that estimates the conditional PDF using time as a predictor (they were interested in modeling nonstationarity due to a time trend), this improves significantly upon the quantile regression. Sankarasubramanian and Lall (2003) extended this to consider multiple climate indices as predictors and compute the conditional PDF.

In this research we propose a conditional GEV approach that is simple, flexible and robust to obtain the conditional PDF incorporating multiple predictors. The approach is first described, followed by its application to two synthetic data sets and an annual maximum flood data. These data sets are same as those in Sankarasubramanian and Lall (2003) so as to enable easy comparison.

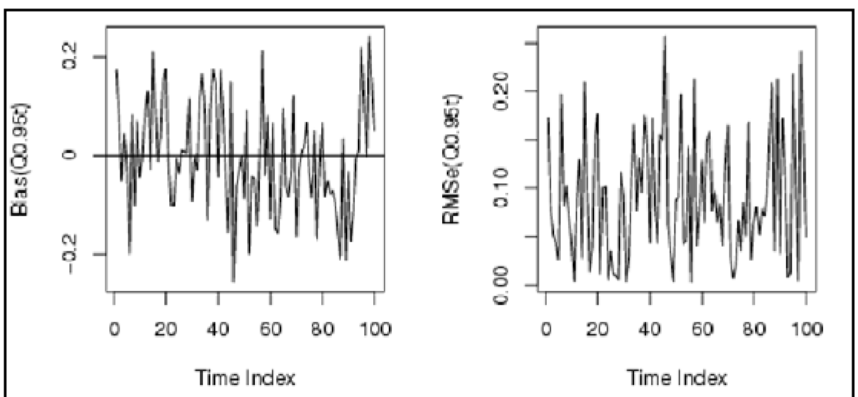

Figure 1. Bias and RMSE for (p=0.95) quantile using the Conditional GEV approach for the homoskedastic simulations.

Conditional GEV Approach

Our proposed approach is based on a Generalized Extreme Value (GEV) distribution model that was developed by Towler et al. (2010) in the context of a water quality application. Below we propose it for hydrologic frequency estimation and the description is abstracted from their paper.

The family of GEV models can be appropriate to fit to data maxima or minima that are taken over long blocks of time (see e.g., Coles, 2001). The cumulative distribution function of the GEV is defined as:

$$G(z;\theta) = \exp\left\{-\left[1+\xi\left(\frac{z-\mu}{\sigma}\right)\right]^{-1/\xi}\right\} \qquad (1)$$

where $\theta = [\mu, \sigma, \xi]$ and $\left[1+\xi\left(\frac{z-\mu}{\sigma}\right)\right] \geq 0$. The location parameter, μ, indicates where the distribution is centered; the scale parameter, $\sigma > 0$, indicates the spread of the distribution; and the shape parameter, ξ, indicates the behavior of the distribution's upper tail (Coles, 2001). Based on the shape parameter, the GEV can assume three possible types, known as the Gumbel, Fréchet, and Weibull. The Gumbel is an unbounded light-tailed distribution ($\xi = 0$), whereby the tail decreases relatively rapidly (i.e., exponential decay). The Fréchet is a heavy-tailed distribution ($\xi > 0$), whereby the tail's rate of decrease is relatively slower (i.e., polynomial decay). The Weibull is a bounded distribution ($\xi < 0$), whereby the tail has a finite value at $z = \mu - \frac{\sigma}{\xi}$ (Coles, 2001). Although several methods can be used for the estimation of the GEV model parameters, here the Maximum Likelihood Estimation (MLE) was utilized for its ability to easily incorporate covariate information (Katz et al., 2002). Here, the unknown parameters, θ, were estimated by maximizing the log-likelihood (*llh*) equation, which is defined as:

$$llh(\theta) = \sum_{i=1}^{N} \log g(z_i;\theta) \qquad (2)$$

The above is 'unconditional' GEV model in that a single model is fitted to the observed data and the quantiles are obtained by inverting Equation (1).

All the distribution fitting methods assume stationarity, in that the observations are independent and identically distributed (*iid*) – which is hard to satisfy in practice. Covariates can be used to account for nonstationarity – for instance, the parameters of the GEV distribution can be modeled as a function of covariates (or predictors) *X*. It is common to model the location parameter as function of covariates which amounts to keeping the shape of the GEV distribution the same but shifted appropriately based on the covariates. The location parameter is modeled as:

$$\mu = X\beta \qquad (3)$$

where the ’s are the intercept and predictor coefficients, which are fitted to maximize the likelihood function (Equation 2). We note that now $\theta = [\beta, \sigma, \xi]$, and that for each time step, μ and the resulting GEV will vary with the covariate(s). Combinations of covariates are selected to model the location parameter above and the best combination is selected as the one that minimizes the Akaike Information Criteria (*AIC*) (Akaike, 1974), which is calculated as:

$$AIC = -2(llh) + 2K \qquad (4)$$

where llh is estimated from Equation 2 and *K* was the number of parameters estimated.

The conditional and unconditional GEV models were fitted using the Extremes toolkit (Gilleland, E. and R. Katz, 2005. Tutorial for the Extremes Toolkit: Weather and Climate Applications of Extreme Value Statistics, http://www.isse.ucar.edu/extremevalues/tutorial/) in the software-language R (http://www.r-project.org).

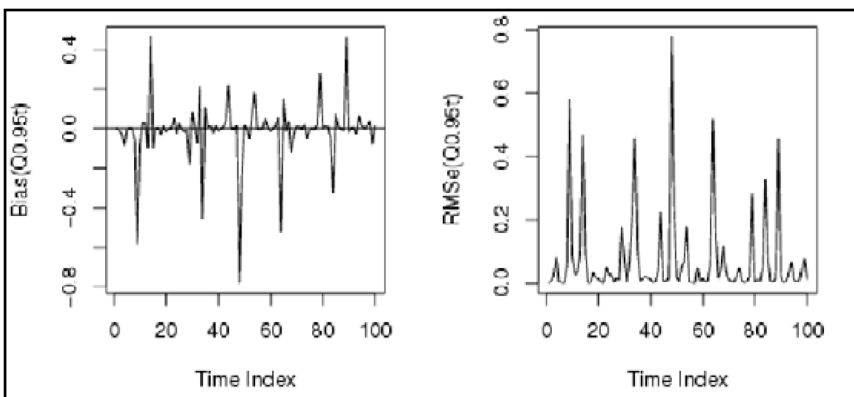

Figure 2. Same as Figure 1. but for the heteroskedastic case.

Evaluation of the Approach

We evaluate the proposed approach on two synthetic data sets and an annual flood data – these are same as those in Sankarasubramanian and Lall (2003) so as to facilitate easy comparison with their methods. The data sets and the results are described below.

Experimental Design of Synthetic Data

An idealized setting of synthetic data designed by Sankarasubramanian and Lall (2003) is to replicate the cyclostationary behavior expected to be present under ENSO and PDO. Two cases are considered: (1) homoskedastic case where nonstationarity is in the mean with a constant variance, and (2) heteroskedastic case where there is nonstationarity in both the mean and variance.

Consider that the annual maximum flood Q_t in year t arises from a lognormal distribution. This corresponds to a model:

$$y_t \approx N\left(\mu_t(t), \sigma_y(t)\right) \quad (5)$$

$$\sigma_{yt} = C$$

where $y_t = \log(Q_t)$, μ_{yt} and σ_{yt} are the mean and the variance of year t.

The parameters of the distribution, for the homoskedastic case, are assumed to vary as:

$$\mu_{yt} = C_1 x_{1t} + C_2 x_{2t} \quad (6)$$

$$\sigma_{yt} = C$$

where C is a constant variance, C_1 and C_2 are coefficients and x_1 and x_2 are two climate predictors.

Similarly, the corresponding parameters for the heteroskedastic case are:

$$\mu_{yt} = C_1 x_{1t} + C_2 x_{2t} \quad (7)$$

$$\sigma_{yt} = C_v \mu_{yt}$$

where C_v is a constant coefficient of variation.

The two predictors are modeled as periodic modes with different frequencies ω_1 and ω_2:

$$x_{1t} = a \, \sin(\omega_1 t + \varphi_1) \quad (8)$$

$$x_{2t} = b \, \sin(\omega_2 t + \varphi_2) \quad (9)$$

where ϕ_1 and ϕ_2 are the phase angles, and a and b are the amplitudes of two climate signals. For this study, a=1.352, b=1.743, ϕ_1=180, ϕ_2=0, T_1=5, ω_1=(2*π/T_1), T_2=18, ω_2=(2*π/T_2), C_1=1.352, C_2=-0.678, C=2 and C_v=0.12.

Using these parameters, we generated 1000 Monte Carlo realizations of x_{1t}, x_{2t} and Q_t, each with a sample size of 100 years (this size was chosen to mimic the data availability in practice). Then using the proposed GEV nonstationary frequency estimation approach cross-validated estimates of the pth quantile that correspond to each year were obtained. The cross-validated Bias and Root mean square error (RMSE) averaged over the 1000 realizations are computed for each time t, as follows:

$$Bias(\hat{Q}_{pt}) = \frac{1}{1000}\sum_{i=1}^{1000}\left[\hat{Q}_{pt}\right]_{-it} - Q_{pt} \quad (10)$$

$$RMSE(\hat{Q}_{pt}) = \sqrt{\frac{1}{1000}\sum_{i=1}^{1000}\left(\left[\hat{Q}_{pt}\right]_{-it} - Q_{pt}\right)^2} \quad (11)$$

Results for Synthetic Data

We computed the cross validated p=0.95 quantile and the Bias and RMSE using the above equations. Figure 1 shows the Bias and RMSE for each time step for the homoskedastic simulations and Figure 2 for the hetroskedastic case. Overall, it can be seen that the Bias and RMSE are smaller for the hetroskedastic case. Furthermore, we can see from Table 1 that the average Bias and RMSE from the conditional GEV approach is very small compared to the traditional quantile regression method and the semiparametric local likelihood. This shows that the conditional GEV approach has the ability to capture effectively the tail behavior even though the simulations were made from Lognormal distribution. The average Bias and RMSE were similarly smaller for other quantiles (not shown).

Annual Flood Data

We applied the conditional GEV approach to the annual flood data from Clark Fork River below Missoula, Montana (USGS Station No: 12353000) for the 1930-2000 period, with a drainage area of 9,003 mi^2 and is minimally affected by upstream activities, diversions and human influence (Slack et al., 1993). For ENSO the average sea surface temperature anomaly in the "NINO3" region in the eastern equatorial Pacific (5N-5S and 150W-90W) was used as the index (available from http://ingrid.ldeo.columbia.edu/SOURCES/.Indices/.nino/.EXTENDED/.NINO3). The PDO index developed by Mantua et al. (1997) is the leading principal component of the monthly SST anomalies in the North Pacific Ocean poleward of 20N. The PDO data sets were acquired from (http://tao.atmos.washington.edu/pdo). The winter (January-February-March-April) average of the NINO3 and PDO indices are used as the predictors of the flood flows (see Figure 3). The correlations ρ(Q,NINO3) and ρ(Q,PDO) are -0.37 and -0.39 respectively. The partial correlations ρ(Q, NINO3|PDO) and ρ(Q, PDO|NINO3) are -0.23 and =0.26 respectively. The null hypothesis of zero correlation is rejected at the 5% significance level for each of these estimates. These correlations indicate that the positive anomalous conditions in both NINO3 and PDO result in low flows and vice-versa. Nonlinear relationship between these climate indices and annual maximum flow was also found by Sankarasubramanian and Lall (2003).

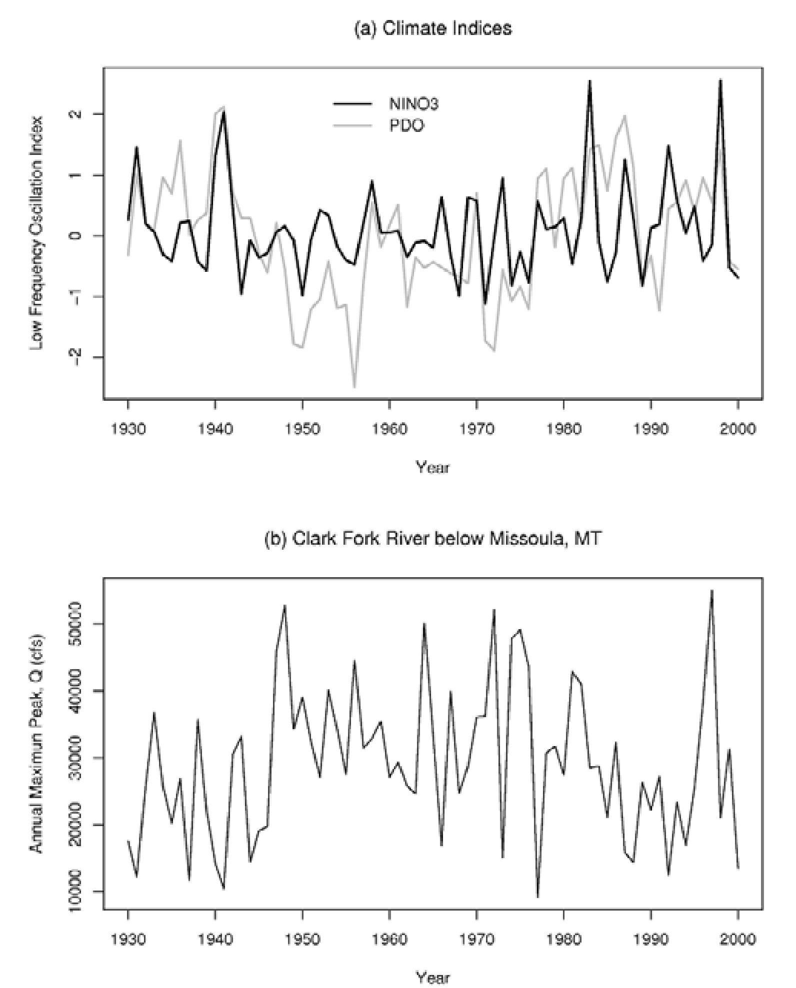

Figure 3. (a) Winter average (Jan-Feb-Mar-Apr) of the NINO3 and PDO indices, (b) Observed annual maximum peak at Clark Fork River below Missoula, MT.

The conditional GEV model was fitted to all of the predictor combinations and using the *AIC* criteria the best model for the location parameter of the GEV was selected and it is given by

The details of the model coefficients and the goodness of fit statistics are shown in Table 2. The diagnostics of residuals from the above model showed a Normal distribution suggesting that the model assumptions are satisfied (not shown).

The fitted conditional GEV model was used to obtain the GEV parameters for each year based on the covariates and consequently, three cross-validated conditional quantiles were estimated: p=0.1, p=0.5 and p=0.9, these are shown in Figure 4. Unconditional (or stationary) quantiles were estimated by fitting a GEV distribution to the entire data and are shown as horizontal lines in this figure. It can be clearly seen that the unconditional quantile estimates are not the best for all the years, given the rich interannual variability in the annual maximum flows. The conditional quantiles shift dramatically from the unconditional values in several of the years. An example can be seen in 1941, where corresponding to positive anomalous conditions in both the tropical and northern Pacific Ocean (NINO3 = 2.03 and PDO = 2.21), the observed flow is one of the lowest and all the conditional quantiles shift significantly lower. Similarly, the quantiles shift up for 1972, which is a high flow year. The key point is that the conditional quantiles capture the variability very effectively. This translates into efficient planning and management of resources. For instance, in a low flow year such as 1941 the quantile forecast from the conditional GEV would indicate a diminished risk of flooding and thus resources could be diverted to plan for droughts and other contingencies – as opposed to stationary quantiles which would indicate a much higher risk of floods and thus divert resources to low probability events. These results compare well with those in Sankarasubramanian and Lall (2003).

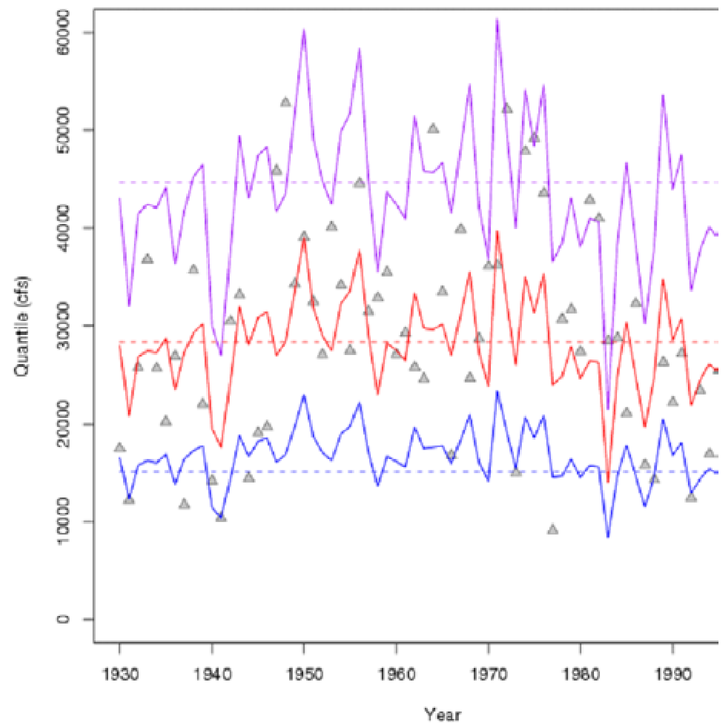

Figure 4. Cross-validated quantiles from the conditional GEV approach. The triangles are observed values, blue line corresponds to p=0.1 quantile, red line to p=0.5 quantile and purple line to p=0.9 quantile. The dashed horizontal lines correspond to the respective unconditional quantiles.

Summary and Discussion

We proposed a conditional GEV approach for nonstationary frequency estimation. In this, the location parameters are modeled as a regression function of covariates, leading to an appropriate GEV distribution for the year, and consequently the quantiles are estimated. Time can also be included as one of the covariates in the regression to capture any temporal trends that might be present. This approach is simple flexible and provides a robust framework to model nonstationarity. As mentioned in the previous section, the potential applications of this approach for seasonal planning and management of resources are immense. This approach can be readily extended to modeling nonstationarity under climate change. For example, using future projections of NINO3 and PDO from global climate models flood frequency projections can be easily estimated. Towler et al. (2010) used this approach to estimate flood frequency projections under climate change for a location in North Western US – in this, they used precipitation and temperature and their nonlinear combination as covariates to develop the conditional GEV model. Future projections of precipitation and temperature from the climate models were used to estimate flood frequency projections and consequently, they translated it to projections of water quality extremes (in this case, elevated turbidity), which is relevant for drinking water managers.

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Biography

Balaji Rajagopalan received his B.Tech. degree in Civil Engineering from the National Institute of Technology in Kurukshetra, India, in 1989. He then received a M.Tech. degree in Optimization and Reliability engineering from Indian Statistical Institute in Calcutta, India, in 1991 and, a Doctorate from Utah State University in Logan, UT, USA, in 1995, with a specialization in stochastic hydrology and hydroclimatology. He was then a Post-Doctoral Research Scientist for two years and then Associate Research Scientist for three years at Columbia University, New York, before joining the faculty at the University of Colorado in Boulder, in 2000. He was promoted to Associate Professor in 2007. He is also a Fellow of the Cooperative Institute for Research in Environmental Sciences at the University of Colorado in Boulder since 2001.

His research focuses on (i) understanding the large-scale climate drivers of year-to-year and multidecadal variability of regional hydrology (i.e., precipitation, streamflow etc.) (ii) developing ensemble hydrologic forecast and simulation tools that incorporate the large-scale climate information (iii) coupling the forecasts with water resources decision support system and, (iv) understanding monsoonal climate variability and predictability. His research has proven to be of immense value in the operations, management and planning of water resources in the semi-arid basins of Western USA. He has also developed tools to quantify uncertainty in input water quality to water treatment plants. He has published over 65 journal articles and has taught courses in Hydraulics, Hydrology, Civil Engineering Design, Hydroclimatology and Statistical methods. He has supervised 6 PhD dissertations and 10 MS thesis. He is also the associate editor of Geophysical Research Letters, Water Resources Research, Climate Research and Journal of Hydrologic Engineering.

Bayesian Nonstationarity Frequency Analysis of Hydrological Variables

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Abstract

The present paper provides a discussion of nonstationary frequency analysis models in hydrology with a focus on the Bayesian approach. The Bayesian model provides an efficient estimation framework of hydrological quantiles in the presence of nonstationarity. In non-stationary frequency analysis models the parameters are functions of covariates, allowing for dependent parameters and trends. The use of the non-stationary Generalized Maximum Likelihood Estimation method (GML) for the prediction of hydrologic data is discussed. This model allows using prior information concerning the variables under study and considering a number of models (linear, quadratic, etc.) of the dependence of the parameters on covariates. A discussion is also provided concerning the use of the reversible jump Monte Carlo Markov Chain (RJMCMC) procedure which allows carrying out the estimation of the posterior distributions of the parameters and the selection of the Bayesian model at the same time. An application to a case study is presented to illustrate the potential of the model.

Introduction

Frequency analysis is a predictive technique that has played an important role in engineering practice. It is based on fitting a probability distribution to a series of observations in order to define the future probabilities of occurrence of a number of events of interest. The selection of the probability distribution that best fits the sample data is usually based on a goodness-of-fit criterion, e.g., Akaike Information Criterion (AIC) (Akaike, 1974). The distribution parameters are estimated using a parameter estimation method such as the method of moments (MM), the maximum likelihood (ML) method or the method of probability weighted moments (PWM).

In hydrological frequency analysis (HFA), it is generally assumed that data is independent and identically distributed (i.i.d) which implies that it must meet the statistical criteria of independence, stationarity and homogeneity. In reality, the probability distribution of extreme events can change with time, indicating the existence of nonstationarity (IPCC, 2001). The criterion of stationarity can then be jeopardized. HFA of non-stationary hydrological variables requires a different approach than the conventional stationary HFA because the distribution parameters change in time and so do the estimates of exceedance probabilities on which are based the design and management of hydraulic structures. In case of nonstationarity, the use of "i.i.d." assumptions to predict the occurrence of design events could lead to catastrophic consequences in case of an underestimation of these events and waste of valuable economic resources in case of their overestimation. Therefore, alternate approaches that incorporate the effects of nonstationarity should be developed and used.

A major advantage of non-stationary models is that they make it possible to include the effect of explanatory covariates of the variable under study directly into classical frequency analysis models. The use of non-stationary HFA models is relatively new and the number of studies is rather small partly because of the non-availability of the appropriate tools to carry out such non-stationary analysis. Other problems related to the implementation of non-stationary models are related to model selection and the complexity of parameter estimation techniques. Indeed, several competing models can be developed and the estimation of the parameters of these models is rather complex as these models contain more parameters than stationary ones. The issue of parsimony becomes, therefore, even more important. The development of robust techniques for model selection and parameter estimation is hence a main issue in non-stationary HFA. Studies that adopted the non-stationary approach for the analysis of hydro-meteorological variables include Cunderlik et al. (2007), El-Adlouni et al. (2007), Hundecha et al. (2008), El-Adlouni and Ouarda (2008, 2009) for local frequency analysis, and Cunderlik and Ouarda (2006) and Leclerc and Ouarda (2007) for regional frequency analysis at ungauged sites. Khaliq et al. (2006) provided an early review of approaches used for the frequency analysis of series of dependant or non-stationary hydro-meteorological variables.

The objective of the present paper is to provide a discussion of non-stationary frequency analysis in hydrology. The remainder of this paper is organised as follows. In section 2, we present a brief introduction to the Bayesian inference framework. Section 3 deals with non-stationary HFA. Section 4 describes the Reversible Jump Markov Chain Monte Carlo algorithm. A case study is presented in section 5. Some conclusions and guidelines for future work are provided in section 6.

Bayesian Estimation

The Bayesian framework (Berger, 1985) is adopted in the present work. In this framework, parameters are treated as stochastic variables in order to account for the imperfect knowledge of their exact values. Aside from using the information provided by the data sample, the Bayesian framework allows to formally incorporate other "prior" sources of information that may be available concerning the parameters of interest. This prior information may be obtained from other studies, regional information, subjective information and expert opinions. Prior information is first used to define the prior probability density of the parameters. This prior distribution must be formulated independently of the observations. The Bayes theorem is then used to update the prior probability density with the observations to obtain the posterior distribution:

$$p(\boldsymbol{\theta} \mid \mathbf{x}) = \frac{f(\mathbf{x} \mid \boldsymbol{\theta})\pi(\boldsymbol{\theta})}{\int f(\mathbf{x} \mid \boldsymbol{\theta})\pi(\boldsymbol{\theta})d(\boldsymbol{\theta})} \quad (1)$$

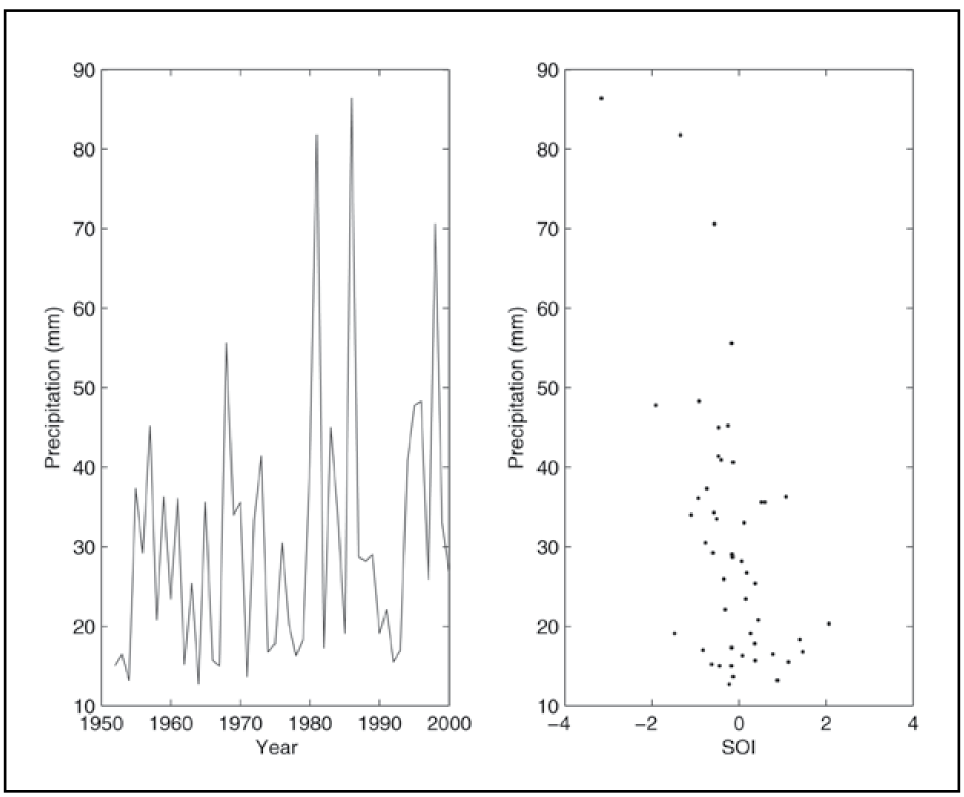

Figure 1. a) Annual maximum precipitation time series at Tehachapi station, and b) scatter plot of observed annual maximum precipitations and corresponding SOI values.

Where x = (x_1, x_2, ..., x_n) is the vector of observations, $\pi(\theta)$ the prior probability density of the parameters, $f(x \mid \theta)$ the likelihood of the observations, and $p(\theta \mid x)$ the posterior probability density of the parameters given the observations. The posterior probability density represents an actualization of the prior knowledge based on the information content of the observations and the model knowledge. For simple problems, the posterior distribution can be obtained analytically. However, in general, sophisticated integration techniques such as Markov Chain Monte Carlo (MCMC) algorithms are used to obtain numerically the posterior distribution.

In the Bayesian framework, model selection is often based on posterior predictive distributions or Bayes factors. Because the Bayes factors are often difficult to compute, a good alternative is to adopt an approximation to the Bayesian Information Criterion (BIC) or the Deviance Information Criterion (DIC).

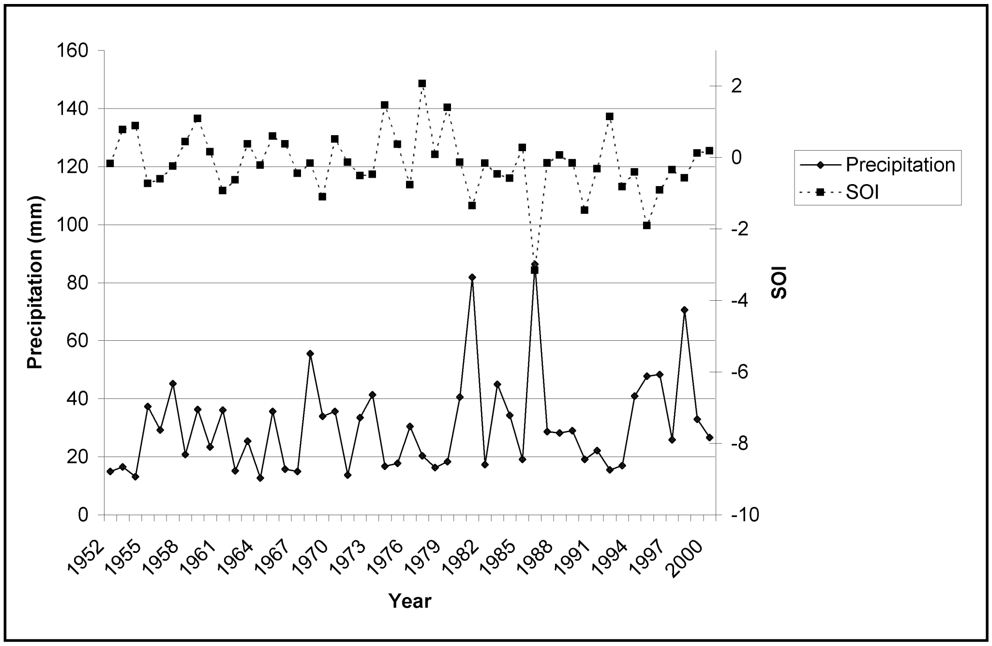

Figure 2. Observed annual maximum precipitation and the SOI index values.

The use of the Bayesian approach in hydrology is associated to several advantages: 1) The interpretation of the results in the Bayesian framework is simple, direct and intuitive and is much simpler than the classical statistical framework. In fact classical statistical concepts, such as confidence intervals, are often falsely interpreted as their Bayesian counterparts, the credibility intervals (Lecoutre, 2005); 2) The Bayesian framework allows incorporating all available sources of information in the inference process. This is especially attractive in HFA for which the number of gauged sites is often limited and the records are often short; 3) It allows to obtain the posterior information concerning the estimates of the parameters but also to evaluate the precision of these estimates; 4) It does not make any asymptotic hypothesis; And 5) it allows handling the various consequences and including the decision process within the statistical inference through cost functions.

In hydrology, the Bayesian inference approach is gaining popularity. The Bayesian framework has been for instance adopted by Davis et al. (1972), Kuczera (1999) and Martin and Stedinger (2000) for hydrologic design, Krzysztofowicz (1983, 1999) for hydrologic forecasting, Reis and Stedinger (2005) for the use of historical information in HFA, Seidou et al. (2006) for the combination of local and regional information in HFA, Seidou and Ouarda (2007) for the detection of nonstationarity and by Beaulieu et al. (2009) for the homogenization of hydro-meteorological variables. The complexity of some of the mathematical developments and the absence of explicit analytical solutions have long represented the main reasons for the lack of use of the Bayesian framework in hydrology. However, recent advances in terms of computational capability and the development of the MCMC numerical integration techniques are leading to an increase in the number of Bayesian applications in the general field of water resources.

Nonstationary HFA

The general procedure for non-stationary HFA will be illustrated for the generalized extreme value (GEV) distribution. The procedure can be adapted to the other families of distributions that are used in hydrology.

The GEV distribution with covariates

The Generalized Extreme Value (GEV) distribution (Jenkinson, 1955) combines the three families of distributions of Gumbel, Fréchet and Weibull. The cumulative distribution function (cdf) of the GEV is:

$$\begin{aligned} F_{GEV}(x) &= \exp\left[-\left(1-\frac{\kappa}{\alpha}(x-\mu)\right)^{1/\kappa}\right] \qquad \kappa \neq 0 \\ &= \exp\left[-\exp\left(-\frac{(x-\mu)}{\alpha}\right)\right] \qquad \kappa=0 \end{aligned} \tag{2}$$

where, $\mu + \alpha / \kappa \leq x < +\infty$ when $\kappa < 0$ (corresponding to the Fréchet distribution), $-\infty < x < +\infty$ when $\kappa = 0$ (Gumbel) and $-\infty < x \leq \mu + \alpha / \kappa$ when $\kappa > 0$ (Weibull). $\mu(\in \mathbb{R})$, $\alpha(> 0)$ and $\kappa(\in \mathbb{R})$ are respectively the location, the scale and the shape parameters of the distribution.

In the presence of nonstationarity, the parameters can be written as function of the explanatory covariates, such as time or low frequency climate oscillation indices: $GEV(\mu_t, \alpha_t, \kappa_t)$ (Coles, 2001). We denote f the probability density function (pdf) of the GEV distribution. A transformation, such as $\varphi_t = \log(\alpha_t)$, is used when estimating the parameters in order to ensure a positive value of the scale parameter. In the general formulation, we assume that the location parameter μ_t is a function of n_μ covariates $U = (U_1\ U_2 \ldots U_{n_\mu})'$. Let $\beta = (\beta_1\ \beta_2 \ldots \beta_{n_\mu})'$ be the vector of hyper-parameters. In the case of linear dependence we have:

$$\mu_t = U'(t)\beta = \sum_{i=1}^{n_\mu} \beta_i U_i(t) \qquad (3)$$

Similarly for the scale parameter α_t and the shape parameter κ_t, let $V = (V_1\ V_2 \ldots V_{n_\alpha})'$ and $W = (W_1\ W_2 \ldots W_{n_\kappa})'$ be the vectors of covariates respectively. We have:

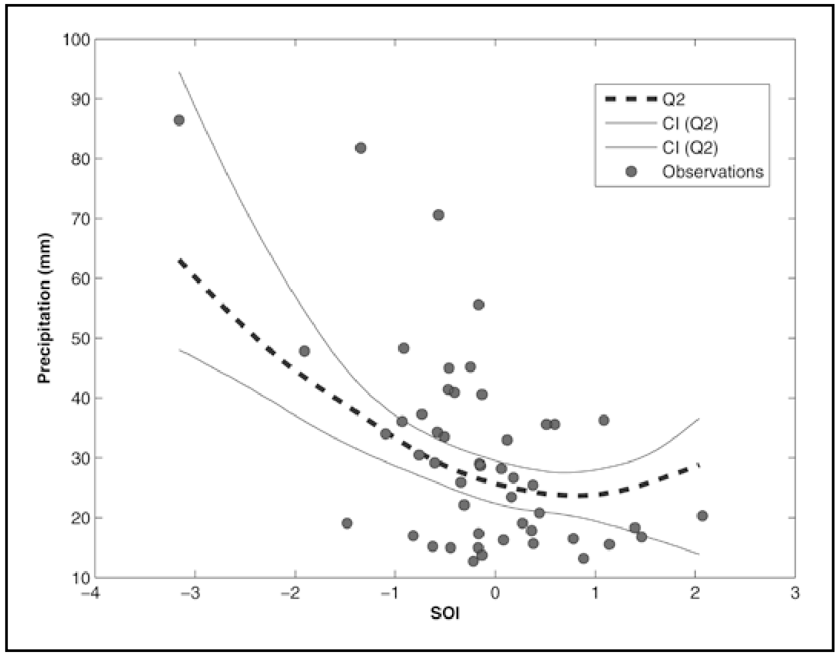

Figure 3. GML estimates of the medians and 95% credible intervals conditional on the values of SOI, obtained with the GEV_{31} model.

$$\varphi_t = \log(\alpha_t) = V'(t).\delta = \sum_{i=1}^{n_\alpha} \delta_i V_i(t) \qquad (4)$$

$$\kappa_t = W'(t).\gamma = \sum_{i=1}^{n_\kappa} \gamma_i W_i(t) \qquad (5)$$

Where $\delta = (\delta_1\ \delta_2 \ldots \delta_{n_\alpha})'$ and $\gamma = (\gamma_1\ \gamma_2 \ldots \gamma_{n_\kappa})'$ are the hyper-parameters respectively.

The likelihood function for a given sample $\underline{x} = \{x_1, \ldots, x_n\}$ is then given by:

$$L_n = \prod_{t=1}^{n} f(x_t \mid \mu_t, \varphi_t, \kappa_t) \qquad (6)$$

Hydro-meteorological data suggest that the shape parameter should be taken to be constant ($\kappa_t = \kappa$). A number of non-stationary models can be considered given the values of n_μ and n_α:

1. $GEV_{1,1}(\mu, \alpha, \kappa)$ represents the classic stationary model: $\mu_t = \mu$, $\alpha_t = \alpha$ et $\kappa_t = \kappa$.
2. $GEV_{2,1}(\mu_t = \beta_1 + \beta_2 Y_t, \alpha, \kappa)$ is the homoscedastic model for which the location parameter is a linear function of one covariate Y_t.
3. $GEV_{2,2}(\mu_t = \beta_1 + \beta_2 Y_t, \alpha = \exp(\delta_1 + \delta_2 Y_t), \kappa)$ is a model for which the location and scale parameters are function of the covariate Y_t.
4. $GEV_{3,2}(\mu_t = \beta_1 + \beta_2 Y_t + \beta_3 Y_t^2, \alpha = \exp(\delta_1 + \delta_2 Y_t), \kappa)$ In this model, the scale parameter is a linear function and the location is a quadratic function of the same covariate Y_t.

Other models can be defined using a vector of covariates. Note that "non-stationary model" is a conventional name for a varying parameter GEV model. Indeed, when covariates are not the time, the studied process may in reality be stationary.

Generalised Maximum Likelihood method

We present herein the Generalized Maximum Likelihood (GML) method for the estimation of the parameters of non-stationary GEV model. The method is based on the maximum likelihood (ML) estimator.

Coles (2001) presented the general description of the covariate approach for the GEV distribution and the ML estimation method. For the sample $\underline{x} = (x_1, ..., x_n)$, the ML estimators of the non-stationary GEV model parameters can be determined by maximizing the likelihood function L_n or the log likelihood function l_n (Coles 2001).

$$l_n(\underline{x};\mu_t,\alpha_t,\kappa) = -n\log(\alpha) - \sum_{t=1}^{n}\left[1-\kappa\left(\frac{x_t-\mu_t}{\alpha}\right)\right]^{1/\kappa} - \sum_{t=1}^{n}\left(1-\frac{1}{\kappa}\right)\log\left[1-\kappa\left(\frac{x_t-\mu_t}{\alpha}\right)\right] \quad (7)$$

Where, n_1 is the number of observations such as $\kappa \neq 0$. We have: $\kappa_t = \kappa$ is a constant. The ML estimators are the solution of an equation system formed by setting to zero the partial derivatives of l_n with respect to each parameter.

The GML method (Martins and Stedinger, 2000) is an extension of the ML Method by adding an additional constraint on the shape parameter in the case of the stationary model $GEV_{1,1}$. Martins and Stedinger (2000) proposed a prior distribution of in the case of the hydro-meteorological variables. A Beta distribution prior for the shape parameter κ $\pi_\kappa(\kappa) = Beta(u = 6, v = 9)$ is then defined. This method was generalized to the non-stationary GEV model by El-Adlouni et al. (2007) by using the same prior for the shape parameter and resolving the ML system generated under this constraint:

$$\begin{cases}\max\limits_{\theta} L_n\left(\underline{x};\theta\right)\\ \kappa \sim Beta\left(u,\mathrm{v}\right)\end{cases} \quad (8)$$

The use of such prior on the shape parameter allows avoiding the stability and convergence problems associated to the ML method. The GML method can be generalized and formulated in a fully Bayesian framework. Indeed, the Bayesian approach gives a convenient and general environment for the integration of any additional information including priors on certain parameters. The GML parameter estimates correspond to the mode of the posterior distributions, which can be computed by numerical methods (Martins and Stedinger 2000). Simulation methods such as Markov Chain Monte Carlo (MCMC) models can alternatively be used to determine the empirical posterior distribution of the parameter vector, and to obtain the marginal distributions of the parameters.

Quantile Estimation

For each parameter, the MCMC method constructs a Markov chain with a stationary and ergodic posterior distribution. After running the Markov chain for a given burn-in period, one obtains a sample from the posterior distribution $\pi(\theta|\underline{x})$. The Markov chain is often constructed via the Metropolis-Hastings (MH) algorithm (Metropolis et al., 1953; Hastings, 1970). The MCMC algorithm produces also the conditional quantile distribution for an observed value, y_0, of the covariate Y_t. Indeed, in the non-stationary framework, quantiles are functions of the covariate values. For each iteration i of the MCMC algorithm, the quantiles $x_{p,y_0}^{(i)}$ corresponding to a non-exceedance probability p, and to the parameter vector $\left(\mu_{y_0}{}^{(i)},\alpha^{(i)},\kappa^{(i)}\right)$, are computed using the inverse of the GEV cdf. For instance, for the $GEV_{m,1}$: case we have:

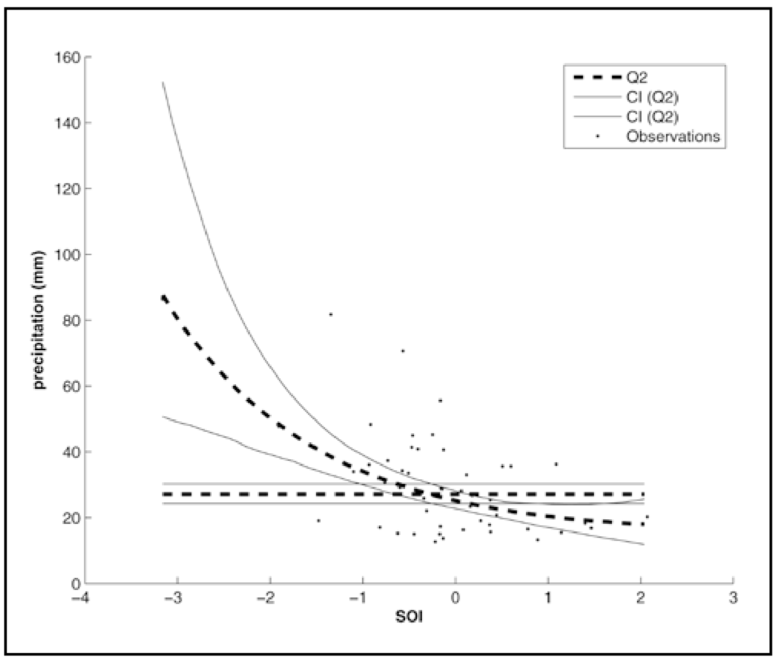

Figure 4. LN2-ML estimates of the medians (quantiles corresponding to the 2-year return period), and 95% confidence intervals conditional on the values of SOI, obtained with the $LN2_{3,1}$ and $LN2_{1,1}$ models.

$$x_{p,y_0}^{(i)} = \left(\mu_{y_0}{}^{(i)}\right) + \frac{\alpha^{(i)}}{\kappa^{(i)}}\left[1-\left(-\log\left(p\right)\right)^{\kappa^{(i)}}\right] \quad (9)$$

Where $\mu_{y_0}^{(i)}$ is the position parameter conditional on the particular value y_0 of Y_t. We have, for instance for the $GEV_{2,1}$ model: $\mu_{y_0}^{(i)} = \beta_1^{(i)} + \beta_2^{(i)} y_0$. From the values $x_{p,y_0}^{(i)}, i = N_0, \ldots, N$, several statistical characteristics of the conditional quantile distribution (such as the mean, the mode or the credibility intervals) can then be determined.

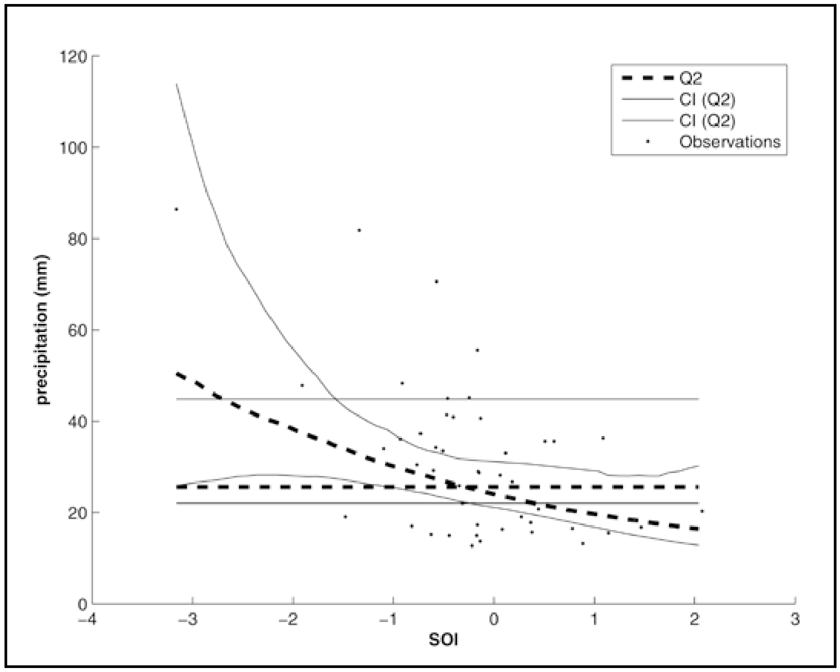

Figure 5. LN3-ML estimates of the medians (quantiles corresponding to the 2-year return period), and 95% confidence intervals conditional on the values of SOI, obtained with the $LN3_{3,1,1}$ and $LN3_{1,1,1}$ models.

Reversible Jump MCMC model

Classical stationary HFA procedure involves the selection of the appropriate statistical distribution and parameter estimation method, the estimation of the values of the parameters and the derivation of the estimates of the desired quantiles. In the non-stationary framework, the number of parameters can increase considerably. Furthermore, the hydrologist has to select the appropriate covariates for the problem in hand, and identify the model of the dependence of the parameters with the covariates (linear, quadratic, etc.). The problem is hence considerably more complex than in the stationary case. This additional complexity can act as a deterrent for the adoption of non-stationary HFA models in hydrological practice. To reduce the level of complexity the derivation of efficient and robust estimation methods is important. One such method is the Reversible Jump MCMC algorithm (RJMCMC) which allows carrying out both model selection and parameter estimation at the same time (Green, 1995, 2003).

The RJMCMC methods allow the jump between models of different dimensions (for example, from the linear dependence model to the quadratic dependence model of the parameters on the covariates). The general algorithm consists of two types of sampling steps. The first one involves dimension-changing moves and the second is conditional on a fixed model. Parameters are estimated in a fully Bayesian framework and the model is selected by the length of time that the MCMC chain remains in that model. El-Adlouni and Ouarda (2009) developed the RJMCMC algorithm for parameter estimation and model selection for the non-stationary GEV models, and illustrated the usefulness of the methodology on real and simulated data sets.

The approach proposed by El-Adlouni and Ouarda (2009) uses RJMCMC to transit between models with different parameter space dimensions. Allowed transitions and corresponding probabilities can be given by :

$$\begin{cases} B_\mu = \text{probability of jump from} \quad n_\mu \longrightarrow n_\mu + 1 \\ B_\alpha = \text{probability of jump from} \quad n_\alpha \longrightarrow n_\alpha + 1 \\ D_\mu = \text{probability of jump from} \quad n_\mu \longrightarrow n_\mu - 1 \\ D_\alpha = \text{probability of jump from} \quad n_\alpha \longrightarrow n_\alpha - 1 \\ C_\mu = \text{probability of jump from} \quad n_\mu \longrightarrow n_\mu \\ C_\alpha = \text{probability of jump from} \quad n_\alpha \longrightarrow n_\alpha \end{cases} \tag{10}$$

For additional information concerning the RJMCMC algorithm the reader is referred to Stephens (2000) or El-Adlouni and Ouarda (2009). The first application of RJMCMC in hydrology was presented by Ribatet et al. (2007) in a regional HFA model.

Case study

The proposed RJMCMC approach is illustrated on a case study that deals with the effect of the Southern Oscillation Index (SOI) on the annual maximum precipitation at the Tehachapi station in Southern California, USA. The Tehachapi (Station 048826) is located at the Latitude 35.13 and Longitude -118.45. The record length is 49 years, extending from 1952 to 2000.

Annual maximum precipitations at the Tehachapi station are strongly affected by the Southern Oscillation Index (SOI). The correlation coefficient between the annual maximum precipitations and SOI takes the value . A total length of was required to ensure the convergence of the Markov Chain. Figure 1 illustrates the annual maximum precipitation time series at Tehachapi station, and the scatter plot of observed annual maximum precipitations and corresponding SOI values. Figure 2 represents the observed annual maximum precipitation and the SOI index values. It is clear that SOI and annual maximum precipitation at the Tehachapi station are in opposition of phase.

The RJMCMC approach allows comparing a large number of models. Results of the application of the RJMCMC algorithm indicate that the $GEV_{3,1}$ represents the most adequate model for the dependence between the annual maximum precipitation and the SOI. Figure 3 illustrates the GML estimates of the medians (quantiles corresponding to the 2-year return period), and 95% credibility intervals conditional on the values of SOI, obtained with the GEV_{31} model. The parameter estimates for the GEV_{31} Model are: $\beta = (21.75\ ;\ -3.59\ ;\ 2.05)$, $\alpha = 10.48$ and $\kappa = -0.10$.

The fact that the GEV31 Model is more adequate than the stationary GEV model indicates that the stationary model leads to relatively large estimation errors. For high annual maximum precipitation years (corresponding to high negative values of SOI), the model leads to significant underestimation of the precipitation quantiles and is hence inappropriate for planning and management purposes.

Additional results are presented for the Tehachapi station for the Log-Normal model with two parameters (LN2) and the Log-Normal model with three parameters (LN3) models to illustrate the flexibility of the non-stationary frequency analysis model with covariates. The ML method is used for parameter estimation. Figure 4 illustrates the LN2-ML estimates of the medians and 95% confidence intervals conditional on the values of SOI, obtained with the $LN2_{3,1}$ model (model with a quadratic scale parameter and a constant shape parameter) and the $LN2_{1,1}$ model (classical stationary LN2 model). Figure 5 illustrates the LN3-ML estimates of the medians and 95% confidence intervals conditional on the values of SOI, obtained with the $LN3_{3,1,1}$ model (model with a quadratic scale parameter and a constant shape and position parameters) and the $LN3_{1,1,1}$ model (classical stationary LN3 model).

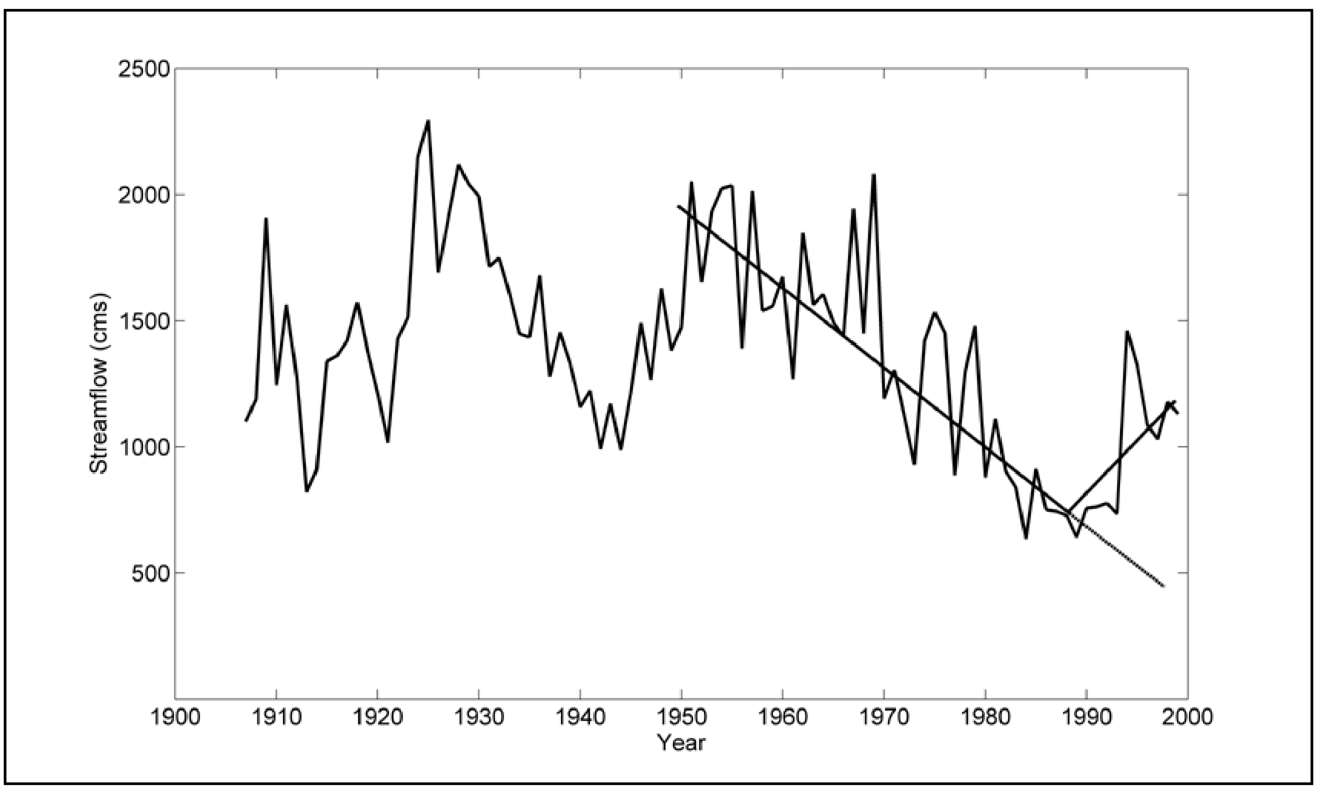

Figure 6. Streamflows at the Koulikoro station on the Niger River Basin, Africa, and errors resulting from direct extrapolation of observed records.

Conclusions

A discussion of the application of non-stationary frequency analysis models with covariates in hydrology is presented. The adaptation of the generalized maximum likelihood (GML) method and the Reversible Jump Monte Carlo Markov Chain algorithm (RJMCMC) for the Bayesian estimation of the parameters of hydrological models with covariates is also discussed. The RJMCMC technique allows jumps between models with different parameter space dimensions. Unlike other approaches presented in the literature to handle nonstationarity, the general model presented herein does not make the assumption of normality. The proposed approach can be applied to more general and more complex models where parameters are expressed as non-linear functions of covariates. The proposed approach is also presented for the annual maximum case but can be adapted for the peaks-over-threshold framework.

The applicability of the proposed approach to design and management problems in water resources is straight forward. The proposed model can be used for instance in hydrogenation planning or the estimation and management of flood risk by conditioning the probability of exceedance on the state of the relevant climate indices. When the covariate is considered to be time, the model can be used to assist in design problems by considering a number of future scenarios. However, it is important to use the model with care. The direct extrapolation of the currently observed trends can be misleading and lead to erroneous results. Figure 6 illustrates the streamflows at the Koulikoro station on the Niger River Basin, Africa. It is clear that the direct extrapolation of the observed trend that was observed during the 1950s, 1960s, 1970s and 1980s in order to build a predictive model as a function of time would have led to wrong results during the 1990s and thereafter. In fact such an extrapolation, by using time as covariate in the non-stationary model and maintaining the same trend, would have quickly led to zero streamflow values in the Niger River at the Koulikoro station. Similarly, the application of the proposed model to the outputs of coupled climate simulation and hydrological models can lead to a false sense of security. These coupled models should be used to provide a number of "*plausible*" scenarios of future evolution.

Another issue that deserves much attention is related to the detection and identification of nonstationarity itself in time series. Indeed, a large number of the techniques used to identify trends (for instance) in hydrological variables assume observations to be independent. The presence of short-term and long-term persistence or cross-correlation between sites has been shown to have a significant impact on the results of trend tests and can result in incorrect estimation of trend significance. This can lead to the adoption of HFA approaches that may be inappropriate for the data under consideration. For more information concerning the identification of trends in the presence of serial and cross-correlation the reader is referred to Hamed and Rao (1998), Koutsoyiannis (2003), Cohn and Lins (2005), Koutsoyiannis and Montanari (2007) and Khaliq et al. (2009a, 2009b). The development and use of Bayesian change detection procedures in hydrology (see for instance Seidou and Ouarda, 2007) can lead to significant advances in this direction.

Future research can focus on the adaptation of the proposed non-stationary approach to regional HFA. Some applications have already been presented in this direction (see Leclerc and Ouarda, 2007; or Ribatet et al., 2007) but much work remains to be done to develop comprehensive regional frequency analysis models that integrate nonstationarity. Future research efforts can also focus on the development of other non-stationary models in hydrology, such as models that use the extremal, r-largest, or point process models with explanatory covariates. Further development of the local likelihood model (Sankarasubramanian and Lall, 2003) and the Bayesian quantile regression method (Yu and Moyeed, 2001 for instance) deserves also much attention.

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Nonstationarity in Precipitation Frequency-Duration Estimates

Geoffrey Bonnin, NOAA, National Weather Service, Office of Hydrologic Development

Abstract

There is popular perception driven by statements in authoritative literature that heavy rainfalls have become more frequent, and that this trend will increase with global warming. Most of the scientific literature examines this question from the point of view of climatology using definitions of "heavy," "very heavy," or "extreme" rainfall, which are different from those commonly used by civil engineers and municipal, state, and federal planners. These differences in meaning have led to a gap in the understanding of the impacts of climate change on precipitation frequency estimates.

This paper identifies the differences in meaning used by the climate and civil engineering communities and examines trends in the observed record in precipitation frequency

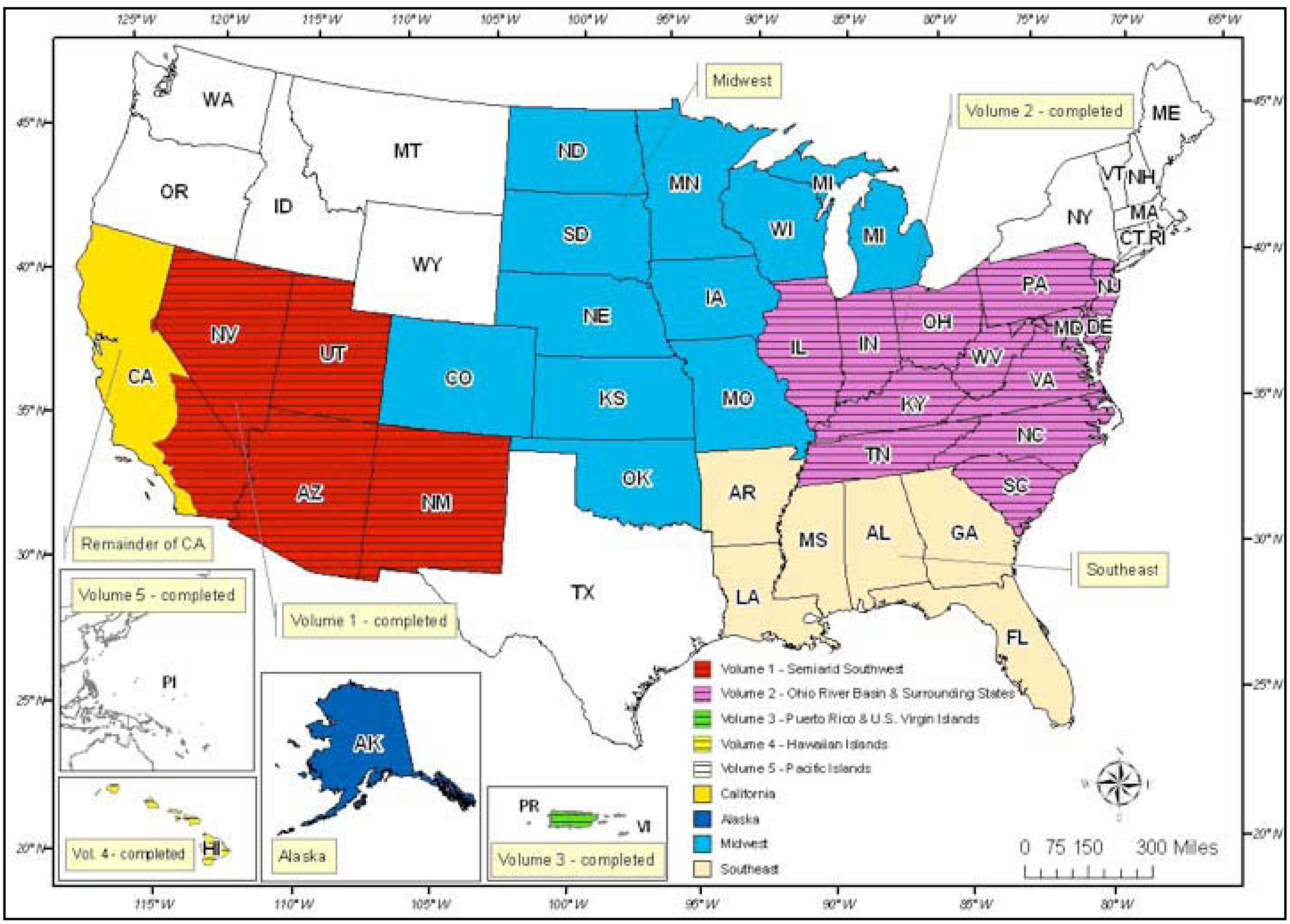

Figure 1. NOAA Atlas 14 Volume Domains.

estimates. We use terms recognized as the basis for design of the nation's civil infrastructure. Specifically, we look at trends in the number of exceedances of thresholds for a variety of precipitation frequencies and event durations, with thresholds taken from Volumes of NOAA Atlas 14, "Precipitation-Frequency Atlas of the United States" (Bonnin et al., 2006a, 2006b). NOAA Atlas 14 provides federal government precipitation frequency estimates for the United States, and is the source of civil engineering, probabilistic design standards for rainfall, and for the regulations issued by many federal, state, and local governments. We quantify observed trends and place them in the context of the uncertainty associated with the precipitation frequency estimates themselves.

Climatology Semantics and Statements: The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4), in its Climate Change 2007: Synthesis Report (IPCC, 2007a) states: "It is likely that the frequency of heavy precipitation events (or proportion of total rainfall from heavy falls) has increased over most areas." The IPCC AR4 Working Group I Report (IPCC, 2007b) states: "Groisman et al. (2005) found significant increases in the frequency of heavy and very heavy (between the 95th and 99.7th percentile of daily precipitation events)." These and similar statements in the literature define terms such as "heavy," "very heavy," or "extreme" precipitation. For example, Groisman et al (2005) state: "For a given location and season, we define a daily precipitation event as heavy when it falls into the upper 10% and/or 5% of all precipitation events; as very heavy when it falls into the upper 1% and/or 0.3% of precipitation events; and extreme when it falls into the upper 0.1% of all precipitation events." They go on to say: "The return period for such events varies depending upon the frequency of days with measurable precipitation and varies, for example, from 3 to 5 years for annual … very heavy precipitation events." We note that these terms generally apply to events of daily durations. While this approach is the predominant one in the analysis of climate change impacts on the frequency of rainfall, some authors for example (Karl, 1998) acknowledge: ".. there is no single method of analysis that can comprehensively cover all the important aspects of how precipitation changes over the course of time .."

Civil Engineering and Civil Infrastructure Planning Semantics: Civil engineers and planners rely on precipitation frequency estimates defined in terms of average annual exceedance probabilities (AEP) or average recurrence intervals (ARI) (otherwise referred to as annual return period or return period). (See Handbook of Hydrology, Maidment, 1992; Bulletin 17B, Interagency Advisory Committee on Water Data, 1982; NOAA Atlas 14, Bonnin, et al., 2004a, b; Australian Rainfall and Runoff, Institution of Engineers, Australia, 1987; Rainfall Frequency Atlas of the Midwest, Huff, 1992). The terms heavy, very heavy, and extreme rainfall are generally subjective terms in civil engineering. Historically, the community has been interested in ARIs ranging from 25 to 100 and 500 years, but in recent decades, with the emergence of design for environmental issues, ARIs down to 1-year and lower have become more relevant. Designs for stormwater drains are typically based on ARIs around 25-35 years, and floodplain management is typically based on ARIs from 100 to 500 years. Large dams are typically designed for the probable maximum precipitation, which has variously been assigned ARIs of 10,000 to 1,000,000 years. These ARIs are far greater than those addressed in the IPCC AR4 reports and in climatology literature.

It is clear then that while the climate community has defined meanings for their descriptions of the magnitude of rainfall, those definitions do not address the much higher rainfall depths and intensities that cause flooding or are of primary concern for the design of civil infrastructure. Furthermore, the meanings assigned to those terms by the climate community are inappropriate given the rainfall depths and intensities that concern the general public and the civil engineering communities. This has led to misinterpretation of statements from authorities such as the IPCC by the civil engineering community (and most likely the general public) and, conversely, a misunderstanding of the information needed for determining the potential impact of climate change on civil infrastructure by the climate community.

We suggest that as we examine the potential impacts of climate change on precipitation frequencies, we use terms, frequencies, and durations in common use for the design and planning of the nation's civil infrastructure. Specifically we should use the terms "average recurrence interval" and "annual exceedance probability," defined in NOAA Atlas 14 (Bonnin et al., 2006a, 2006b), Australian Rainfall and Runoff (Pilgrim, 1997), and recommended for use by the U.S. National Research Council (National Research Council, 2000).

Calculating Exceedances

We attempt to bridge the semantic gap by extending the analyses of the climate community into the range of greater rainfalls, which cause flooding and are of interest for the design of civil infrastructure. In order to root ourselves in the semantics and design standards of the civil engineering community, we have used the specific precipitation frequency estimates provided in NOAA Atlas 14 Volumes 1 and 2 as thresholds. We have counted and analyzed the number of exceedances of these thresholds in the historical record. As shown in Figure 1, Volume 1 provides estimates for the

Duration	ARI (yr)	Semiarid Southwest N	t-test	SpearR	MannK	Ohio Basin and Surrounding States N	t-test	SpearR	MannK
6 hours	1	61	0	0	0	60	0	0	0
	2	61	0	0	0	60	0	0	0
	5	61	0	0	0	60	0	0	0
	10	61	0	0	0	60	0	0	0
	25	61	0	0	0	60	0	0	0
	50	61	0	0	0	60	0	0	0
	100	61	0	0	0	60	0	0	0
1 day	1	105	1	1	1	116	0	0	0
	2	105	1	1	1	116	-1	-1	1
	5	105	1	1	1	116	-1	-1	1
	10	105	1	1	1	116	-1	-1	1
	25	105	1	1	1	116	-1	-1	1
	50	105	1	1	1	116	-1	-1	1
	100	105	1	1	1	116	-1	-1	1
2 days	1	105	1	1	1	116	0	0	0
	2	105	1	1	1	116	0	0	0
	5	105	1	1	1	116	0	0	0
	10	105	1	1	1	116	0	0	0
	25	105	1	1	1	116	0	0	0
	50	105	1	1	1	116	0	0	0
	100	105	0	1	1	116	-1	0	0
4 days	1	105	1	1	1	116	0	0	0
	2	105	1	1	1	116	0	0	0
	5	105	1	1	1	116	0	0	0
	10	105	1	1	1	116	0	0	0
	25	105	1	1	1	116	0	0	0
	50	105	0	1	1	116	0	0	0
	100	105	0	1	1	116	0	0	0
7 days	1	105	1	1	1	116	0	0	0
	2	105	1	1	1	116	0	0	0
	5	105	1	1	1	116	0	0	0
	10	105	1	1	1	116	0	0	0
	25	105	0	1	1	116	0	0	0
	50	105	0	1	1	116	0	0	0
	100	105	0	1	1	116	0	0	0
20 days	1	105	0	0	0	116	0	0	0
	2	105	1	0	0	116	0	0	0
	5	105	1	1	1	116	0	0	0
	10	105	1	1	1	116	0	0	0
	25	105	0	1	1	116	0	0	0
	50	105	0	1	1	116	0	0	0
	100	105	0	1	1	116	0	0	0
45 days	1	105	0	0	0	115	0	0	0
	2	105	0	0	0	115	0	0	0
	5	105	0	0	0	115	0	0	0
	10	105	0	0	0	115	0	0	0
	25	105	0	0	0	115	0	0	0
	50	105	0	1	1	115	0	0	0
	100	105	0	0	0	115	0	0	0

Table 1. Significance Test Results
1 = statistically significant positive trend
-1 = statistically significant negative trend
0 = statistically not significant

semiarid southwest U.S., and Volume 2 provides estimates for the Ohio River Basin and surrounding states. These domains are of roughly the same size and somewhat the same locations as the regions used by Groisman (2005). In addition to daily durations, we also examined events of 6-hour and 2-, 4-, 7-, 20-, and 45-day durations.

For each station in the NOAA Atlas 14 Volume 1 and Volume 2 domains, and for durations of 6 hours and 1, 2, 4, 7, 20, and 45 days, we counted the actual number of exceedances in the available historic record, treating the historic records as partial duration series for consistency of the statistics. We counted exceedances for thresholds associated with average recurrence intervals of 1, 2, 5, 10, 25, 50, 100, 200, 500, and 1,000 years. The thresholds in NOAA Atlas 14 were calculated using careful choices of extreme value probability distribution functions and the method of L-moments to parameterize the functions (see Bonnin et al, 2006a, 2006b and Hosking and Wallis, 1997). This approach is different from the approach adopted by most authors in the climate community who generally use thresholds defined as a percentile of daily series. For example, see Groisman (2005) and Karl (1998).

We calculated the sum of the exceedances over all stations in each domain in each year, duration, and for each ARI. We then normalized for the varying number of stations with observations in each year by dividing by the number of stations with observations in each year. The resulting value for each domain, year, ARI and duration is the average number of exceedances per station per year. This number should be similar to the expected value, which can be calculated from the ARI. For example, for an ARI of 25 years, we can expect an average of four exceedances per station per century, for an ARI of 50 years we can expect an average of two exceedances per station per century, and for an ARI of 100 years we can expect an average of one exceedance per station per century.

We utilized trend-testing statistical procedures to decide whether there were statistically significant trends in the time series (see Helsel and Hirsch, 2005; Hirsch et al., 1982; Haan 2002). The ability of a test statistic to discern the presence of a trend may be impacted by the distribution type and the shape parameter of the probability distribution. Therefore, it was important to make a comparison of results from different test statistics.

In this study, two rank-based non-parametric statistical tests (cf. Khaliq et al., 2009, and Helsel and Hirsch, 2005 and references therein); namely the Mann-Kendall test (MannK), Spearman's rho test (SpearR), and the parametric t-test (Haan 2002) are used to assess the significance of trend in the exceedance's time series. These test statistics were applied to each frequency-duration-based series at a significance level of 0.05 (i.e., $\alpha = 0.05$). Table 1 shows the results of the significance tests for both the semiarid southwest and the Ohio River Basin and surrounding states. The result of the test is returned as: $T_d = 1$, indicating positive trend); $T_d = -1$ indicating negative trend; or $T_d = 0$, indicating failure to detect a significant trend.

For the semiarid southwest domain, the slopes are generally statistically significant except for 6-hour and most 45-day durations, but with some exceptions as shown in the table. For the domain of the Ohio River Basin and surrounding states, the slopes are not statistically significant except for daily durations of 2-years ARI and above.

Figures 2 through 15 show the plotted data with the regression lines for each combination of domain and duration. The figures were not plotted from the beginning of the historic record because of the small number of stations in the early years. The starting point for the plots was chosen subjectively based on the number of stations recording data in particular years.

Rates of Change

The linear regressions represent the average rate of change in the number of exceedances over the period for which they are calculated. They are expressed as a percentage of the expected value to be able to compare slopes. For example, a 100-year ARI event can be expected once per century, and a 50-year ARI event twice per century on average. An increase of 3 in the number of exceedances per station per century results in 1+3=4 100-year ARI events per station per century and 2+3=5 50-year events per station per century. Expressed as a percentage of the expected value, this yields an increase of 4/1=400% and 5/2=250% respectively.

Figures 16 and 17 show the average rates of change for the stations in the semiarid southwest and the Ohio River Basin and surrounding states, respectively, for each frequency and duration. There were not a sufficient number of exceedances of 200, 500, and 1,000-year ARI thresholds for meaningful rates of change, and so we have not included them.

Figure 16 shows that for the semiarid southwest, the rate of change in the number of exceedances for all durations and frequencies tends to be very small: between +0.4% and -0.5% per station per century. The daily duration decreases as much as 1% for ARIs of 50 and 100 years.

Figure 17 shows that for the Ohio River Basin and surrounding states, the rate of change in the number of exceedances for all durations and frequencies tends to very small increases: below 0.5% per station per century. The daily duration increases as much as 1% for ARIs of 50 and 100 years.

These trends are small with respect to the uncertainty associated with estimating precipitation frequency. The greatest rate of change is -1% for the 1-day and 50- and 100-year ARI cases in the semiarid southwest, and +1% for the same events in the Ohio River Basin and surrounding states. A rate of change of 1% per station per century is the equivalent of changing a 100-year ARI event to 99.01 or 101.01-year ARI. The 90% confidence intervals provided in NOAA Atlas 14 range from the order of +/- 30% of the mean in sparsely instrumented areas with shorter periods of record to +/- 10% in areas with more dense instrumentation and longer periods of record. Figure 18 illustrates a +/- 1% rate of change per station per century against a typical intensity, duration, and frequency curve drawn with the upper and lower 90% confidence intervals. It shows that such a rate of change, even though the largest found in this study, is still very small when compared with the error associated with the estimates themselves. Because the rates of change in frequency of precipitation of primary relevance for flooding and for civil engineers are small with respect to our ability to accurately define those estimates, civil engineers and planners should be considering this uncertainty in addition to considering any potential future changes in the estimates.

Conclusion

The literature in the climate community examining potential impacts of climate change on rainfall frequencies uses terms, which on their face appear to address the frequencies required by those who plan and account for those impacts on the nation's civil infrastructure. However, because of differences in semantics, this literature does not properly address precipitation frequencies important to the nation's civil infrastructure. It further appears that at least in the historical record, the uncertainty associated with the estimates is of much greater importance than changes in the estimates over time in the historical precipitation record. We suggest that as we examine the potential impacts of climate change, we use terms, frequencies, and durations in common use for the design and planning of the nation's civil infrastructure. Specifically, we should use the terms "average recurrence interval" and "annual exceedance probability." We also suggest that the potential impacts of climate change on precipitation frequency should be evaluated against frequencies and durations that are associated with design and planning.

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Biography

Geoffrey Bonnin is Chief of the Hydrologic Science and Modeling Branch of the National Weather Service, Office of Hydrologic Development. He manages science and technique development for flood and stream flow forecasting and water resources services provided by the National Weather Service. The work of the group includes development and maintenance of U.S. precipitation frequency estimates. Geoff initiated the development of NOAA Atlas 14 and was lead author for the first three volumes.

Geoff Bonnin graduated B.E. (Civil) from the University of Queensland, Australia and M.S. (Engineering Management) from the University of Kansas. He is a Chartered Member of the Institution of Engineers Australia and a member of the American Society of Civil Engineers. He has extensive experience in flood forecasting and flood forecast systems development with the U.S. National Weather Service and the Australian Bureau of Meteorology. He also has extensive experience in software engineering and systems integration in private industry. His primary areas of expertise are in data management as the integrating component of end-to-end systems, the science and practice of real time hydrologic forecasting, estimation of extreme precipitation climatologies, and the management of hydrologic enterprises. Mr. Bonnin is one of the developers, and the primary implementer, of Standard Hydrometeorological Exchange Format (SHEF).

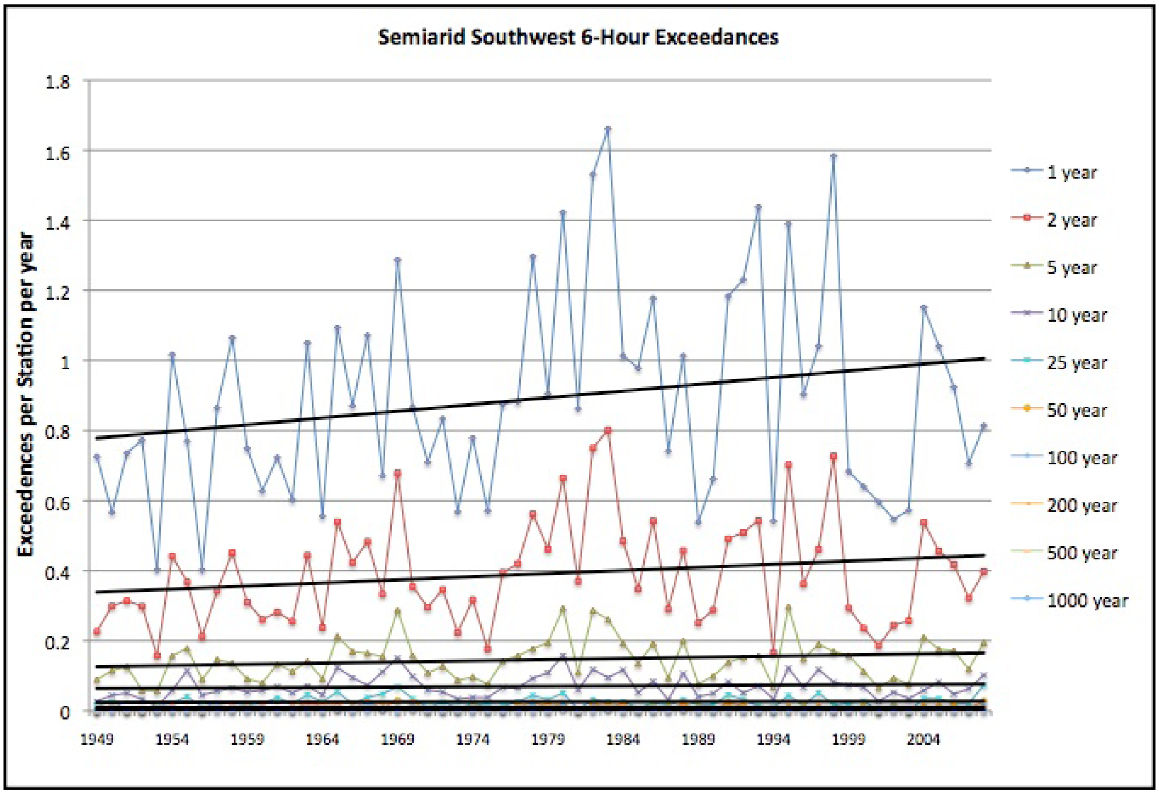

Figure 2. Semiarid Southwest 6-Hour Exceedances.

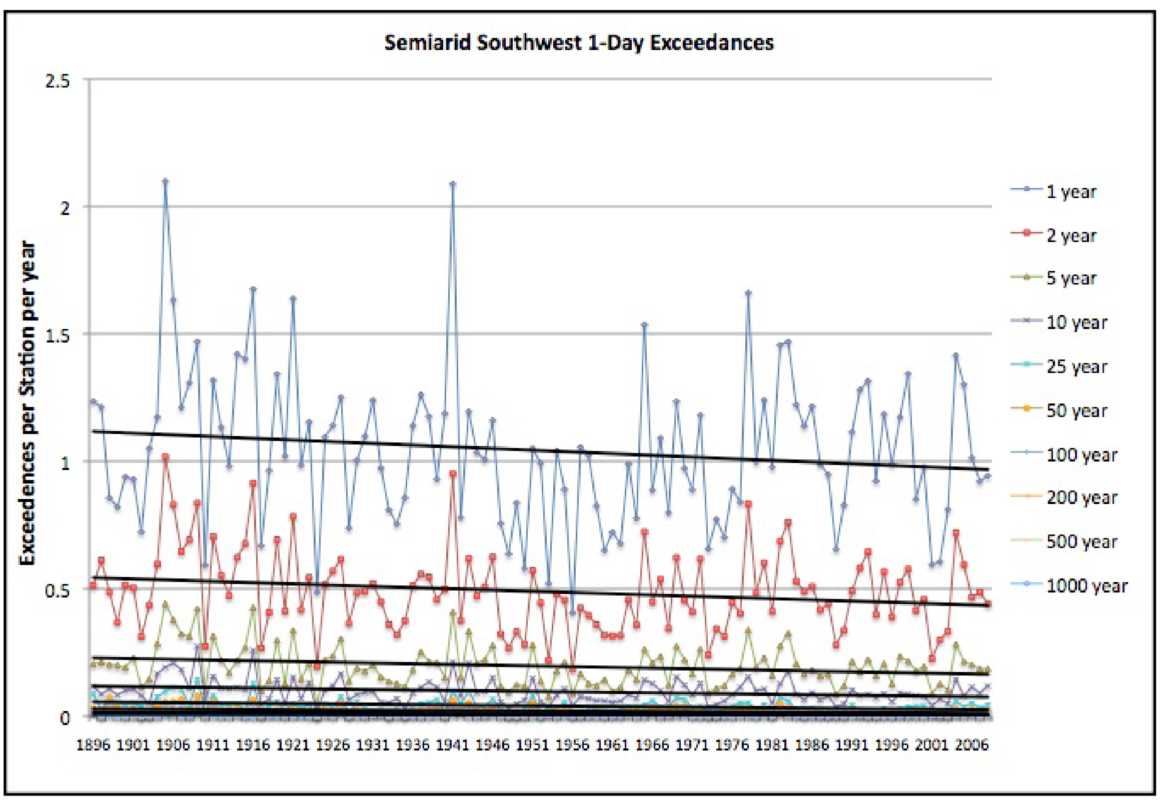

Figure 3. Semiarid Southwest 1-Day Exceedances.

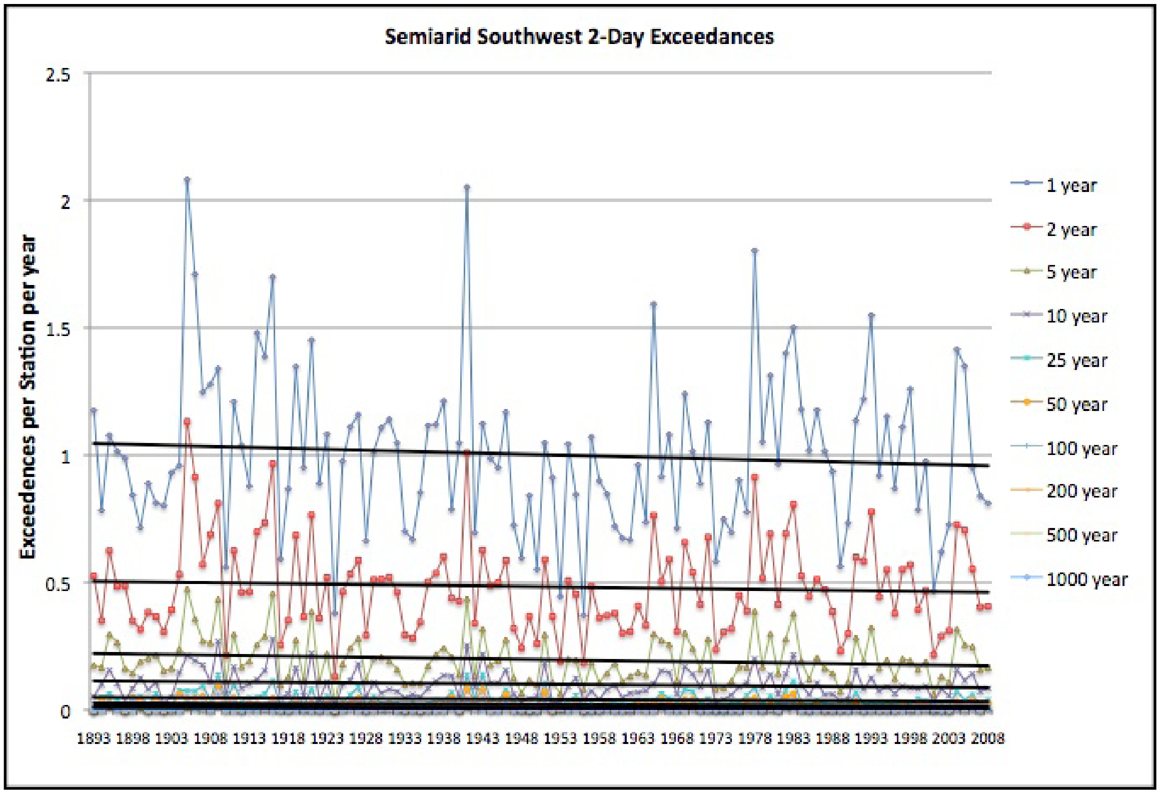

Figure 4. Semiarid Southwest 2-Day Exceedances.

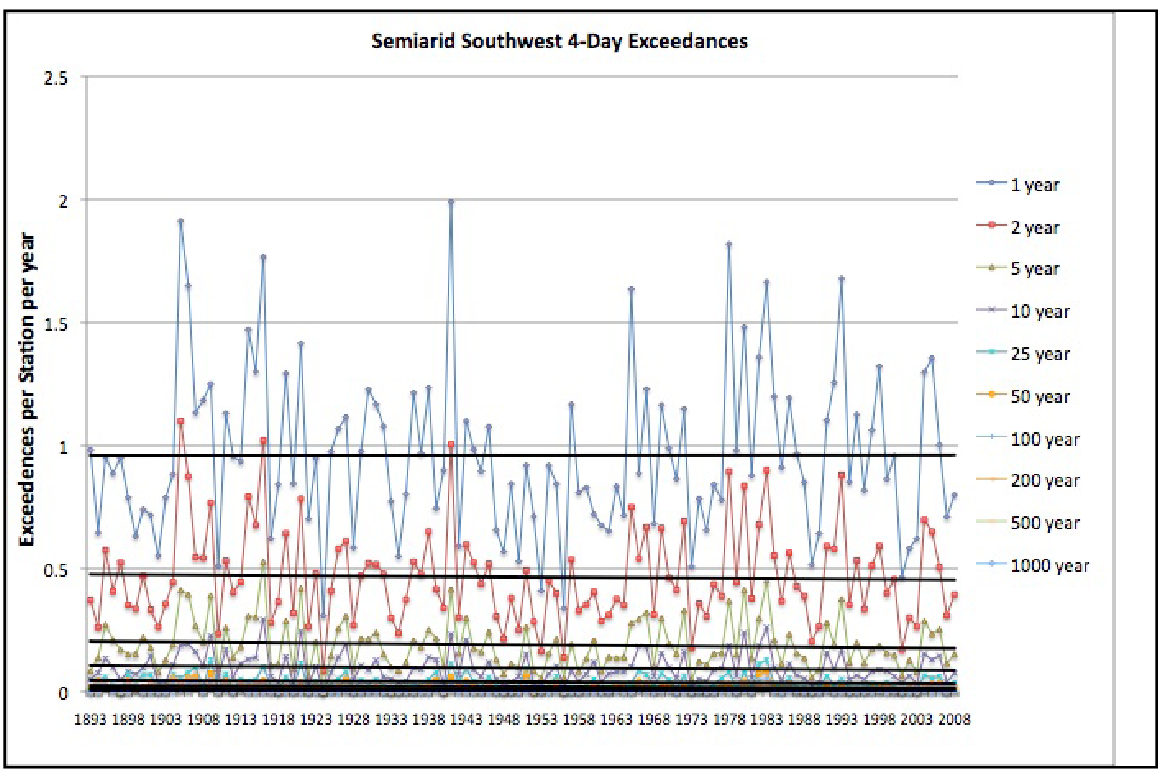

Figure 5. Semiarid Southwest 4-Day Exceedances.

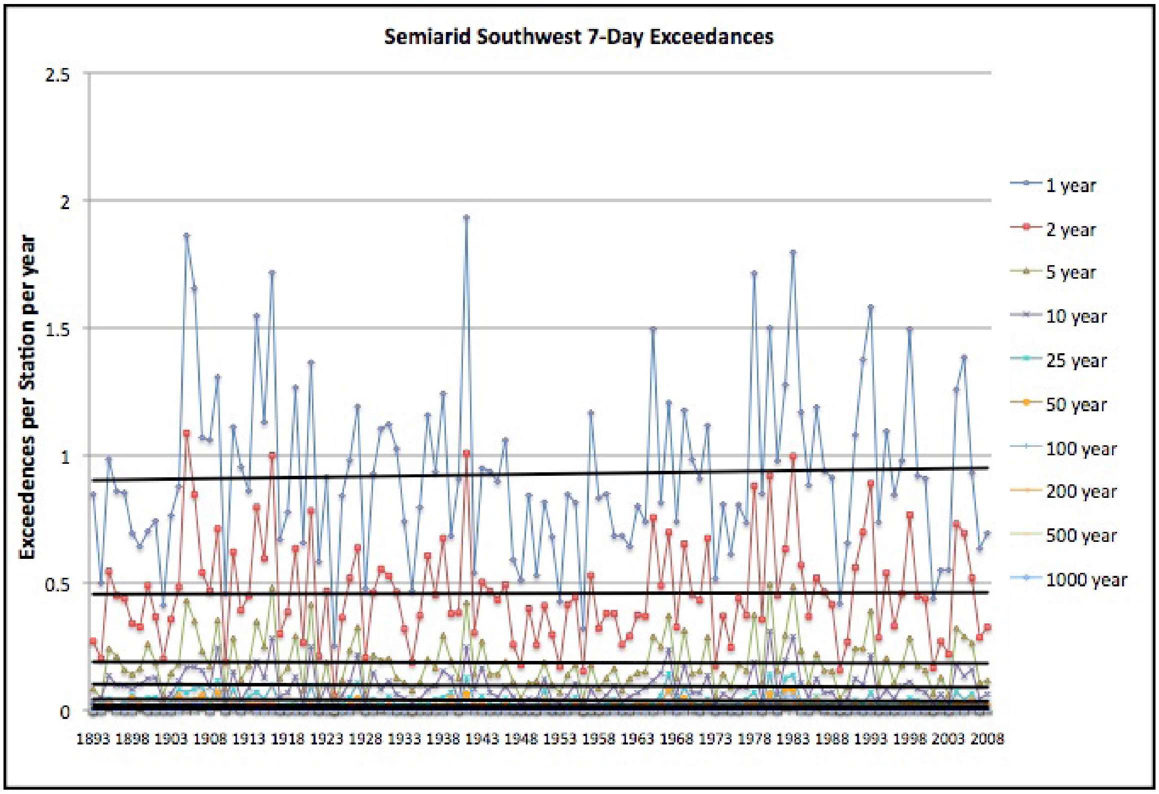

Figure 6. Semiarid Southwest 7-Day Exceedances.

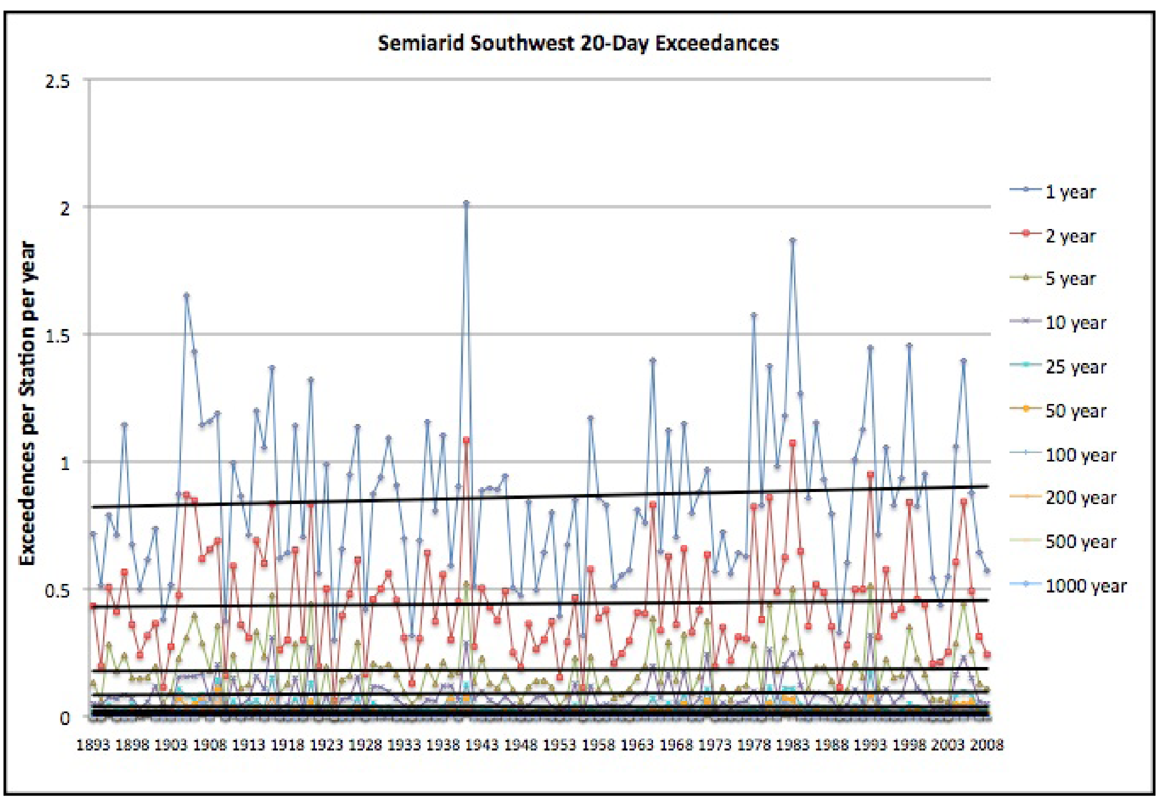

Figure 7. Semiarid Southwest 20-Day Exceedances.

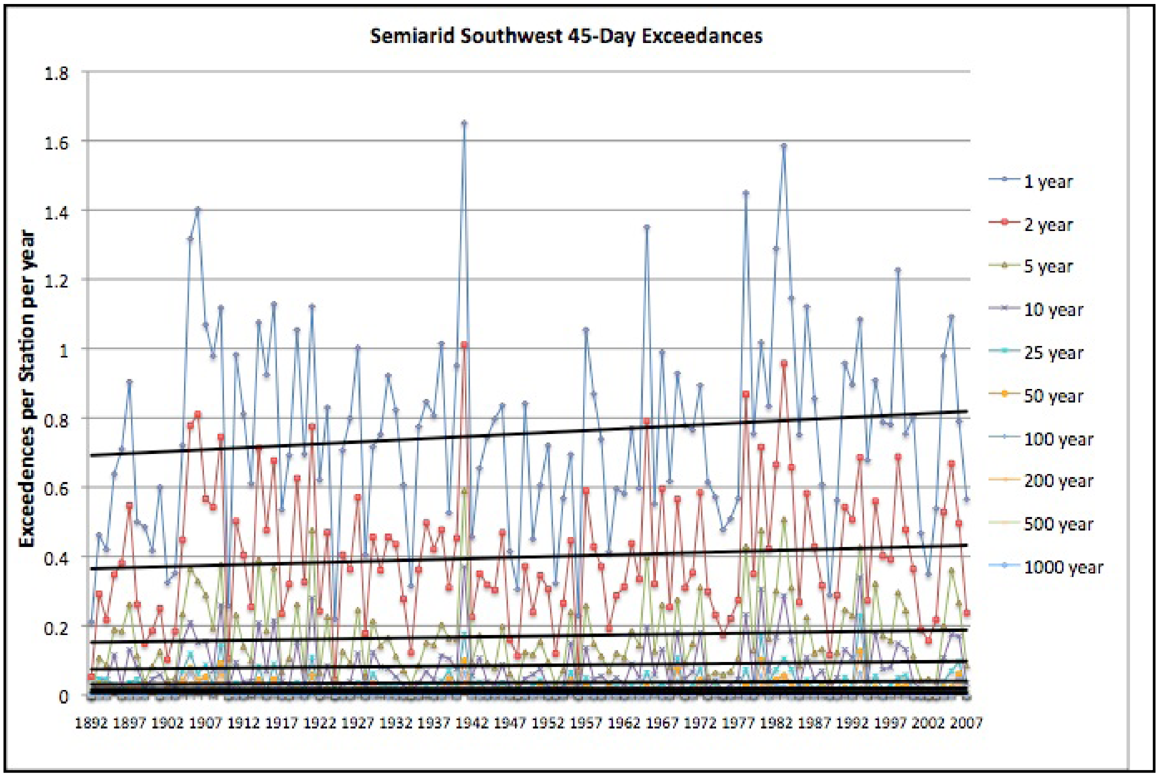

Figure 8. Semiarid Southwest 45-Day Exceedances.

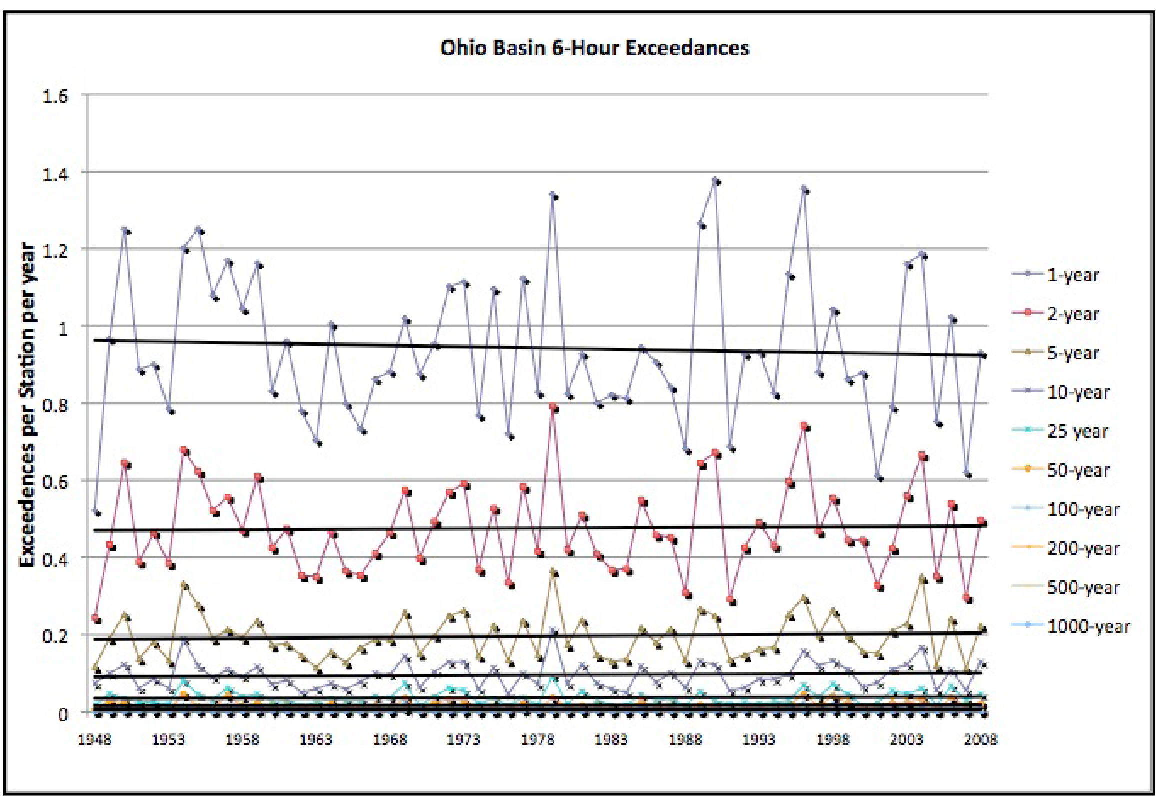

Figure 9. Ohio Basin 6-Hour Exceedances.

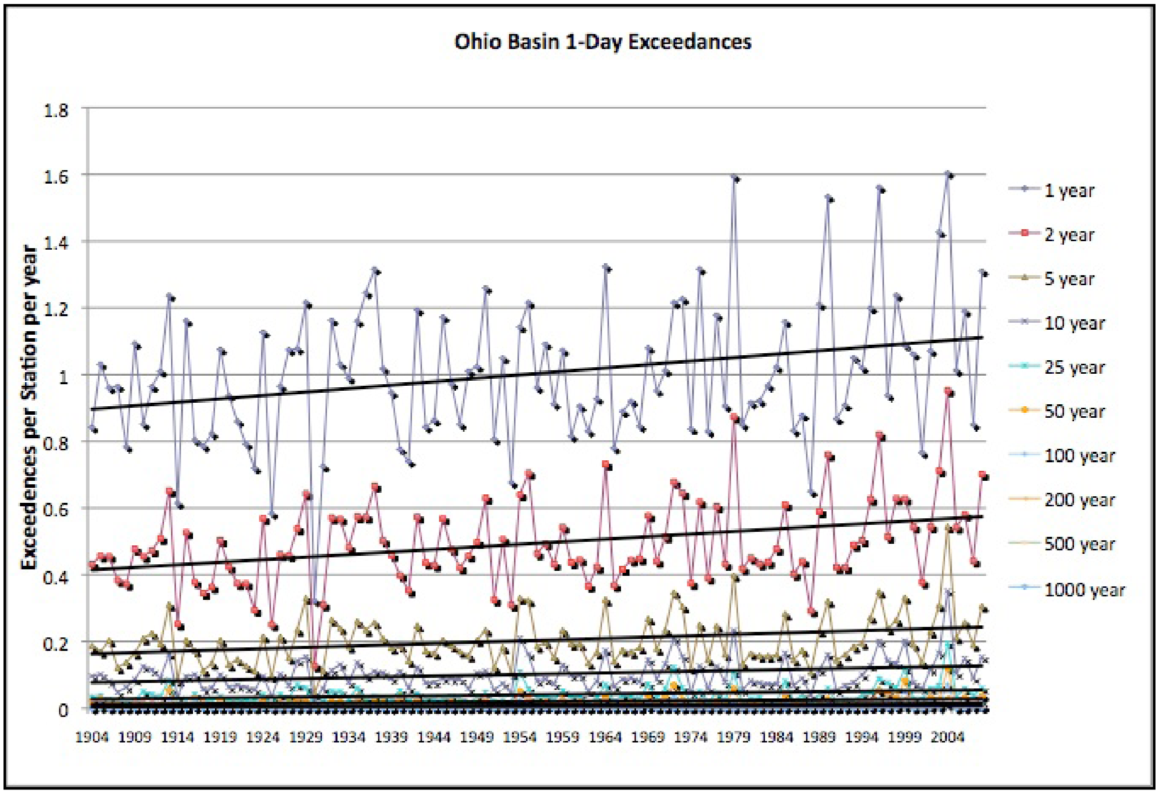

Figure 10. Ohio Basin 1-Day Exceedances.

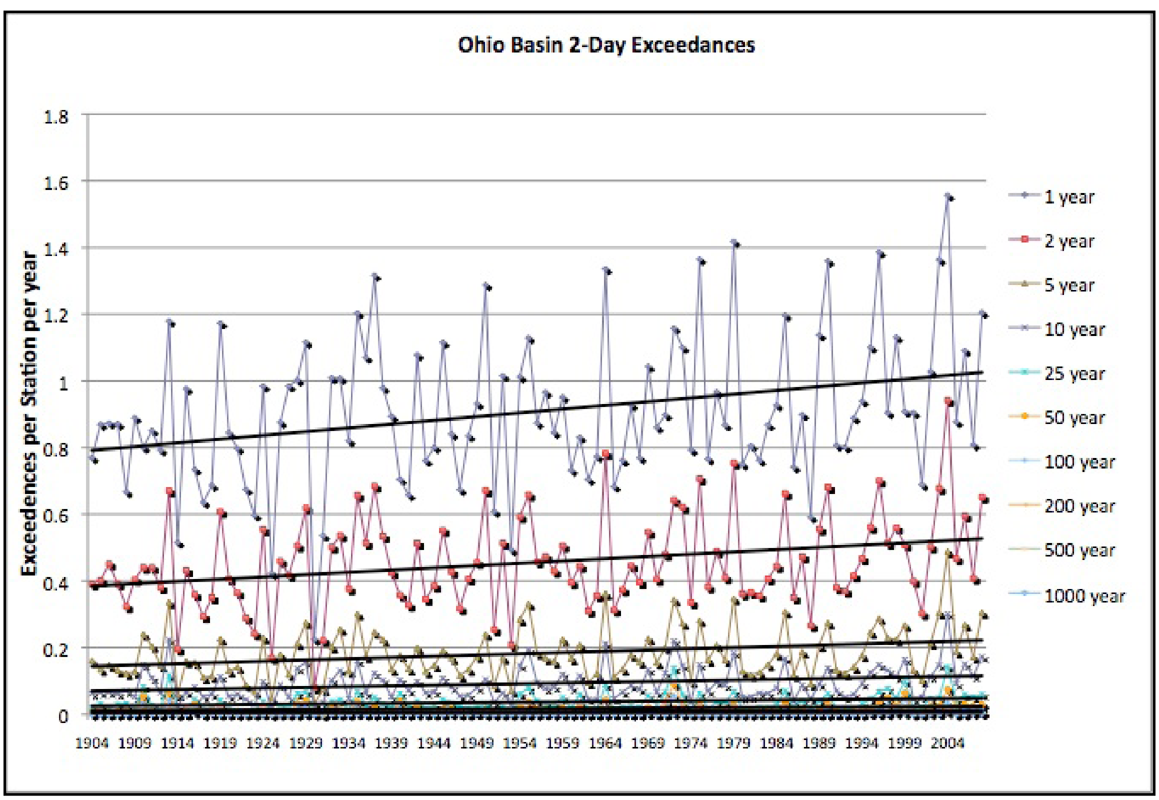

Figure 11. Ohio Basin 2-Day Exceedances.

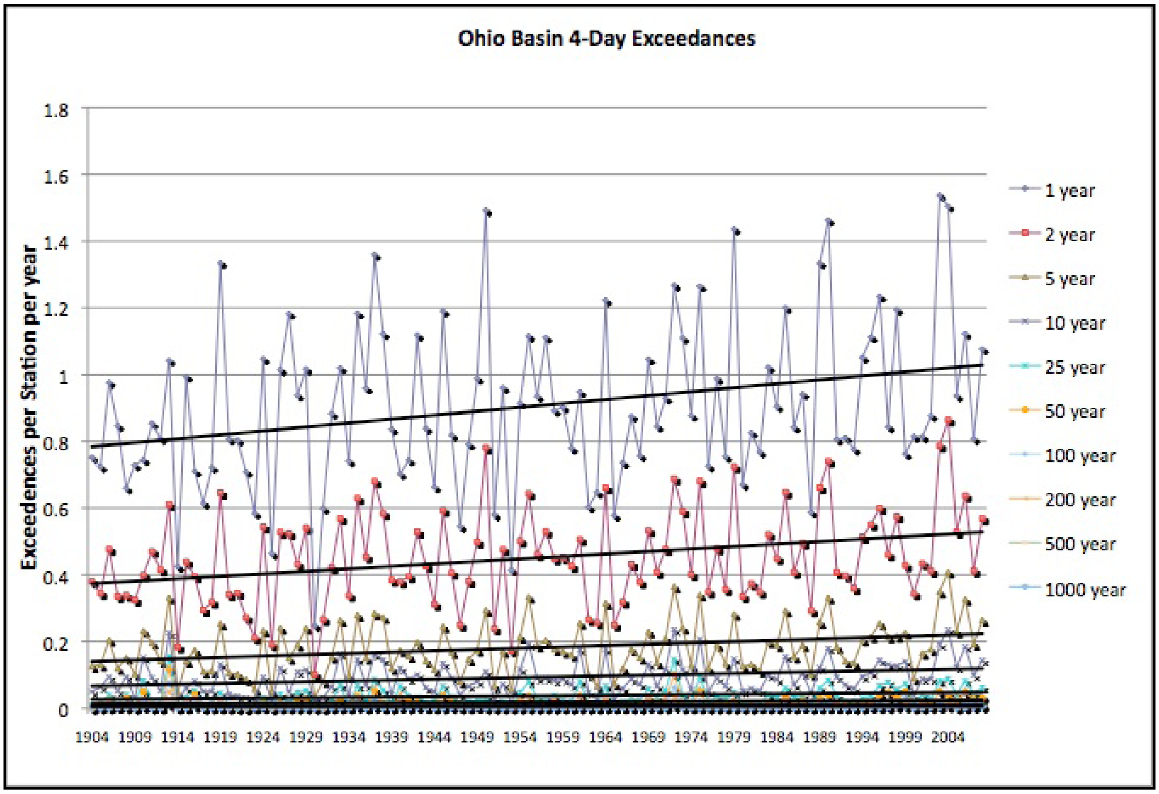

Figure 12. Ohio Basin 4-Day Exceedances.

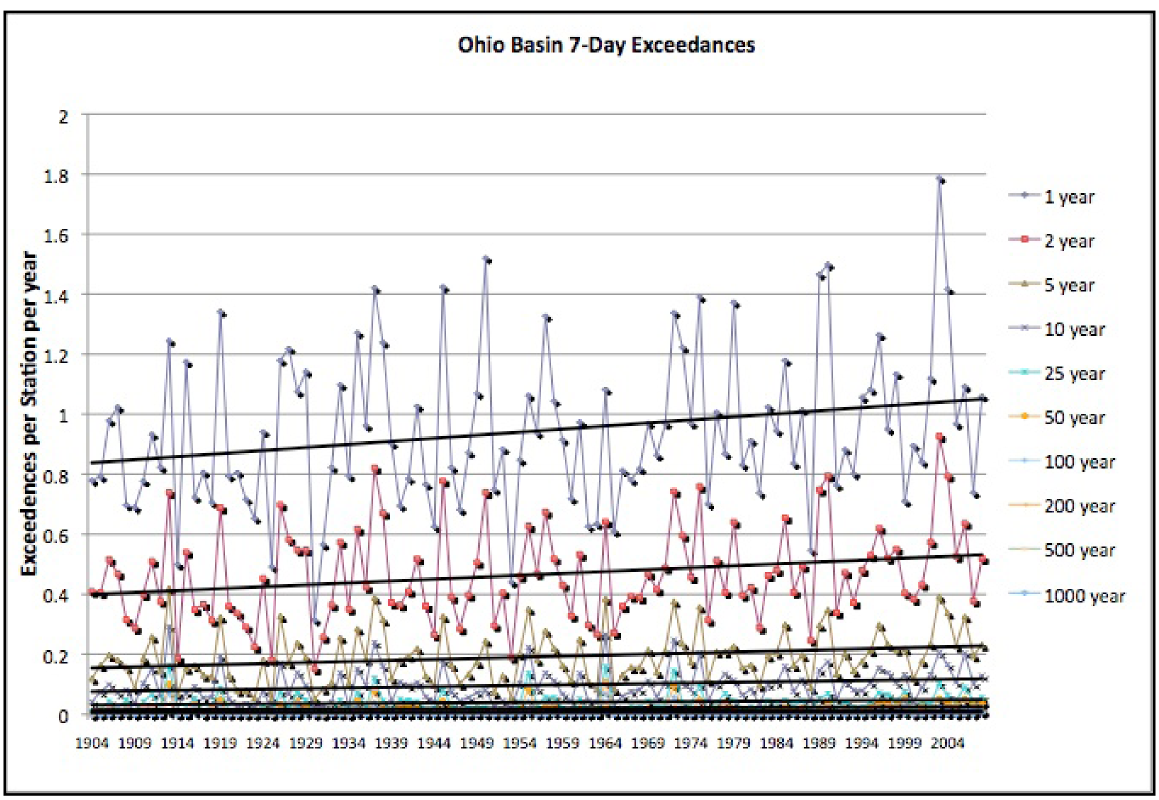

Figure 13. Ohio Basin 7-Day Exceedances.

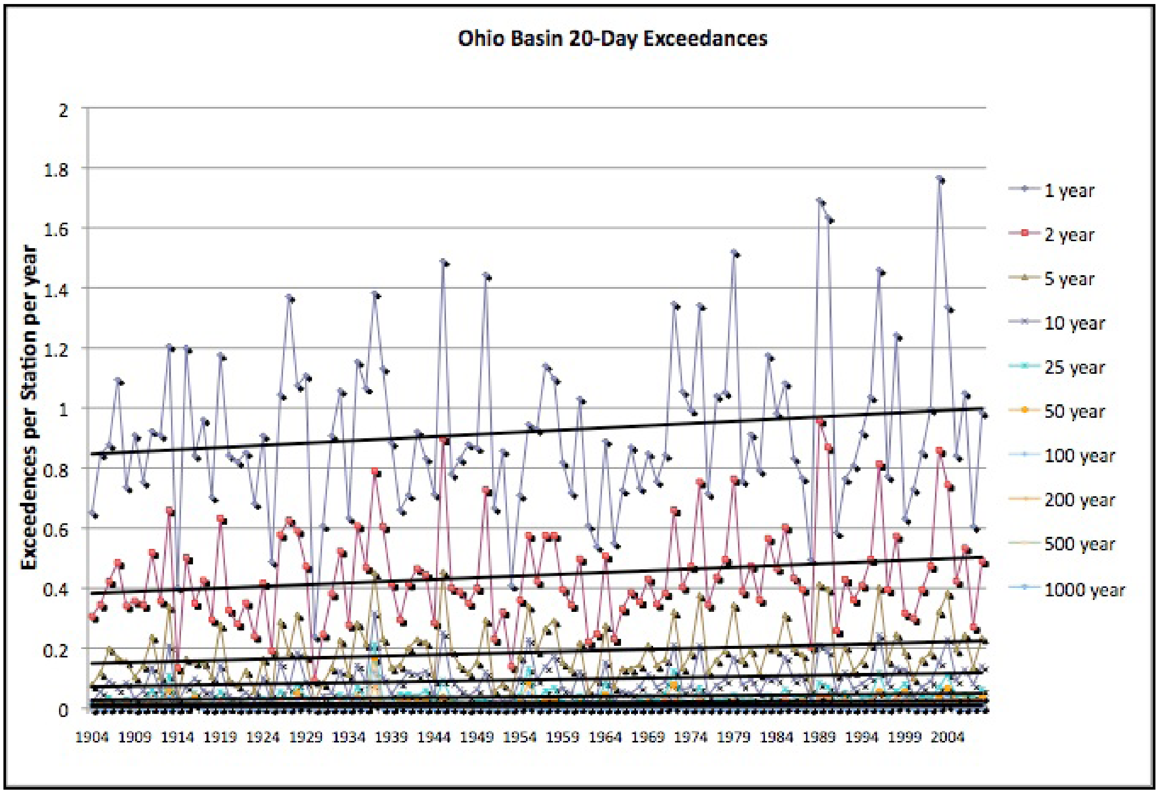

Figure 14. Ohio Basin 20-Day Exceedances.

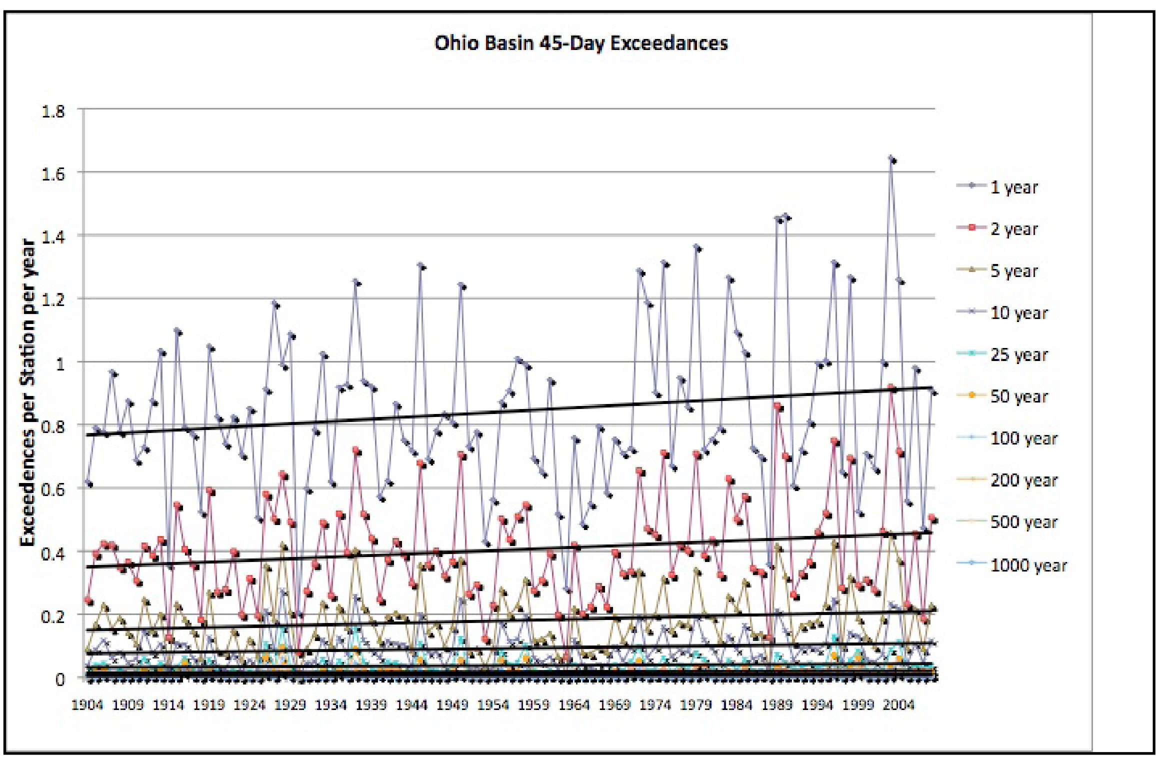

Figure 15. Ohio Basin 45-Day Exceedances.

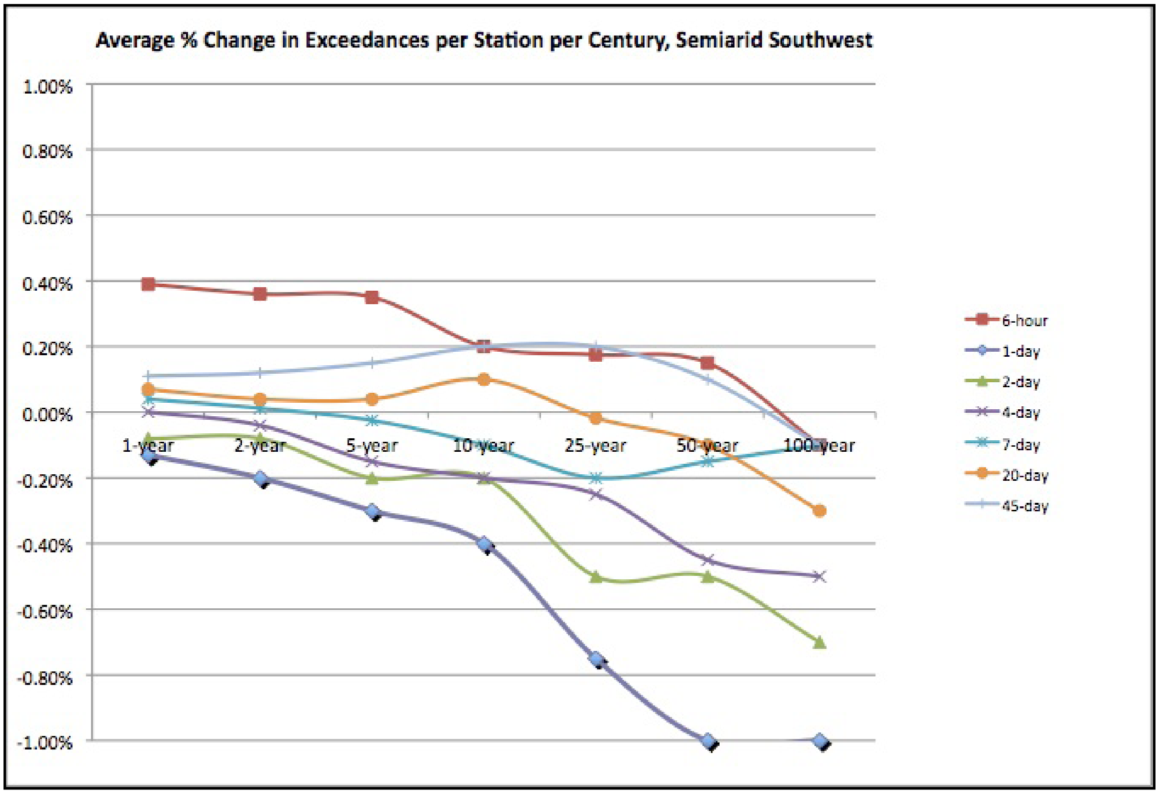

Figure 16. Average Percentage Change in Exceedances per Station per Century for the Semiarid Southwest Study Area.

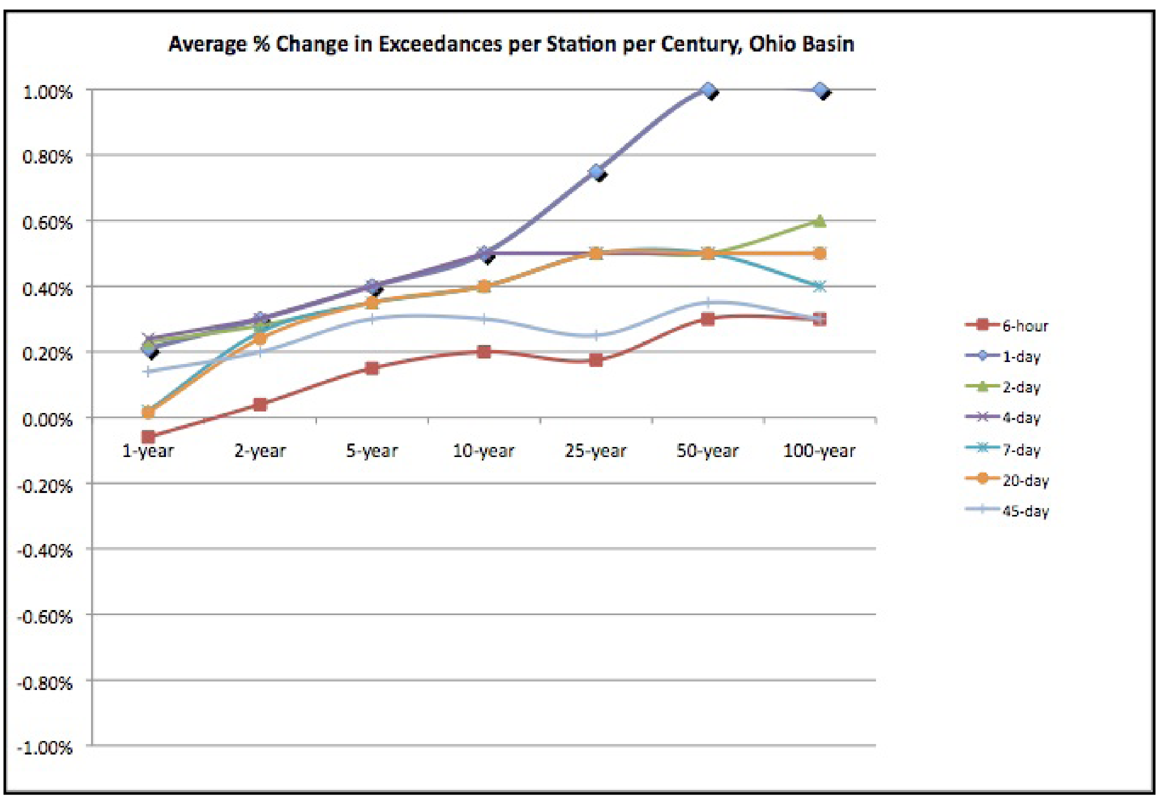

Figure 17. Average Percentage Change in Exceedances per Station per Century for the Ohio River Basin and Surrounding States Study Area.

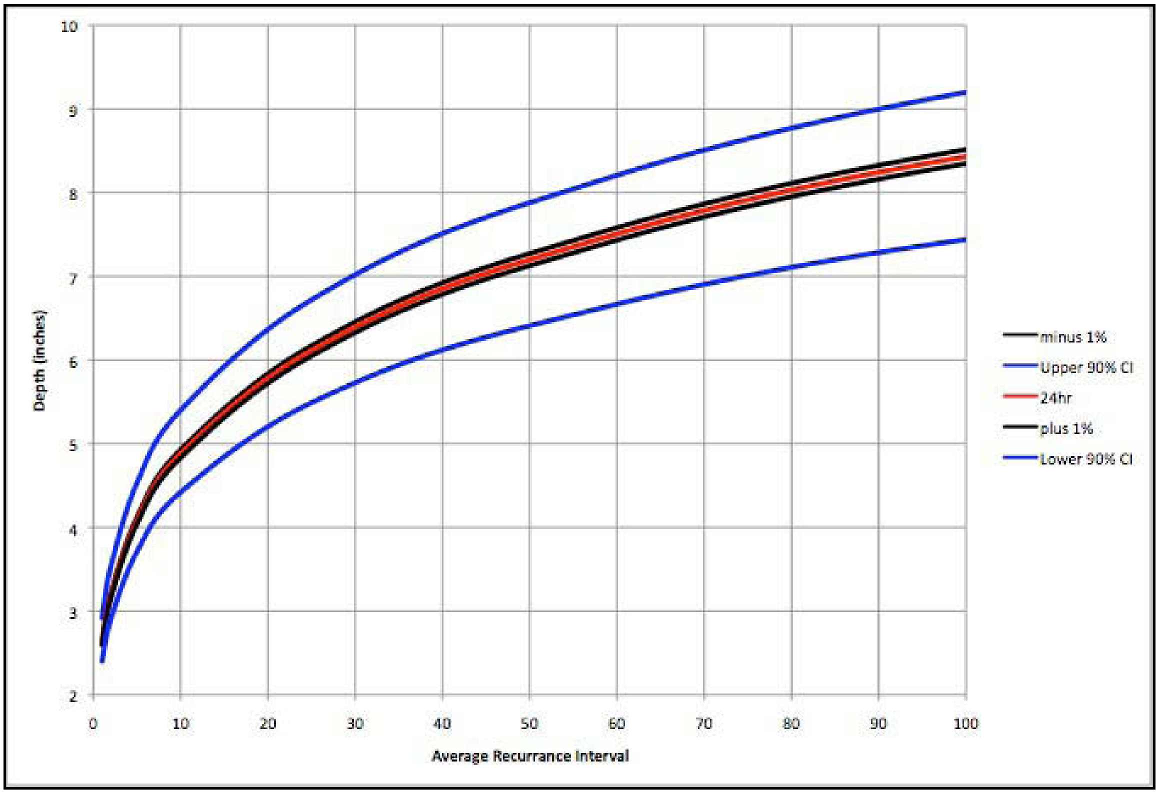

Figure 18. The effect of a 1% increase or decrease in exceedances per station per century is very small compared with the upper and lower 90% confidence intervals about the precipitation frequency estimates.

Flood Magnification Factors in the United States

Richard Vogel, Tufts University

Abstract

It is no longer possible to consider streamflow as a stationary process, yet nearly all existing methods for the planning, management and operation of water resource systems assume that the stochastic properties of historical streamflow will remain unchanged in the future. In the few instances when trends in extreme events have been considered, most previous work has focused on the influence of climate change, alone. This study takes a different approach by exploring trends in floods in watersheds which are subject to a very broad range of anthropogenic influences, not limited to climate change. A simple statistical model is developed which can both mimic observed flood trends as well as the frequency of floods in a nonstationary world. This model is used to explore a range of flood planning issues in a nonstationary world. A decadal flood magnification factor is defined as the ratio of the T-year flood in a decade to the T-year flood today. Similarly, a recurrence reduction factor is defined as the reduction in the average recurrence interval between floods resulting from nonstationarity. Using historical flood data across the entire U.S. we obtain typical flood magnification factors in excess of 2-5 for many regions of the U.S. particularly those regions with higher population densities. Importantly, nonstationarity in flood flows is shown to result from a variety of anthropogenic processes including changes in land use, climate and water use, with likely interactions among those processes making it very difficult to attribute trends to a particular cause.

Introduction

It is no longer possible to consider streamflow and other hydrologic processes as stationary processes (Milly et al., 2008). Nearly all of the methods developed for the planning, management and operation of water resource systems assume stationarity of hydrologic processes. Nonstationarity can result from a myriad of human influences ranging from agricultural and urban land use modifications, to climate change and modifications to water infrastructure. Most studies which sought to detect trends in hydrologic processes focused on the influence of climate change, alone. This study takes a different approach by exploring trends in floods in watersheds which are subject to a very broad range of anthropogenic influences, not limited to climate change. The primary goal of this study is to explore the implications of changes in extreme events which result from all possible anthropogenic influences. A simple statistical model is developed which can both mimic observed flood trends as well as the frequency of floods in a nonstationary world. This model is used to explore a range of flood planning issues in a nonstationary world.

Numerous studies which have explored trends in annual maximum floods in the continental United States. Villarini et al. (2009) provides a recent review of the conflicting conclusions drawn by various studies, some of which found increases, some decreases and others concluded that there were no significant trends in annual maximum discharge across the continental U.S.. A variety of good reasons are given in the literature to help us understand such conflicting scientific claims. For example, Douglas et al. (2000) and others have documented that when one properly accounts for the spatial correlation among flood series, that what often appear to be significant trends, end up being insignificant when the proper statistical approaches are employed. Thus we now know, from the results of Douglas et al. (2000) that there are numerous previous studies which mistakenly concluded that they found significant trends in flood series simply because they did not properly account for spatial correlation among the series. Similarly, Cohn and Lins (2005) show how one can easily confuse long term persistence with trends, so that a series which exhibits long term persistence, which is a stationary stochastic process, may be interpreted as one which exhibits a trend. Thus for a variety of reasons, stationary series can easily be mistaken for nonstationary series. In an effort to avoid confusion of long term persistence with detection of monotonic trends, Villarini et al. (2009) only examined flood records of length 100 years or greater, for 50 stations across the US. Interestingly, in spite of the long records they analyzed, combined with the fact that many of the records they considered exhibited significant regulation effects, they concluded that no trends were apparent. Importantly, they also noted that results of change point detection analyses could further confound our ability to detect monotonic trends, yet another reason why stationary series can be confused with nonstationary series, and vice versa.

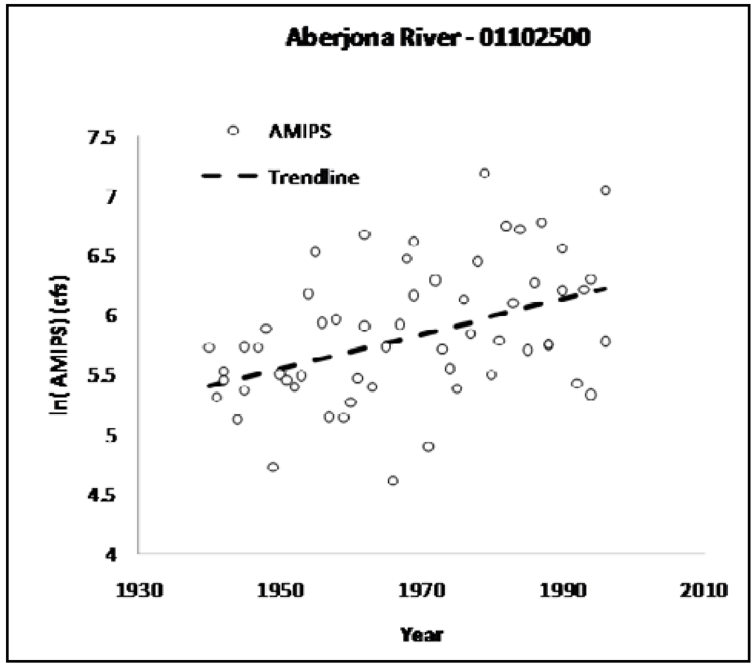

Figure 1. Example of trend in the logarithms of the AMIPS for Aberjona River in Massachusetts ($\hat{\beta}$ =0.0146)

Small et al. (2006) provide additional reasoning for why so few previous studies have reported trends in annual maximum flood series. Many previous studies have reported that total precipitation is increasing across the United States with most of those increases resulting from a positive trend in the upper tail of the daily precipitation distribution. Other studies have found that low and moderate, but not high flows, are also increasing across much of the United States. Small et al. (2006) document why precipitation produced by intense events can increase without a corresponding increase in high flows. They show that a large fraction of the trends in annual precipitation can be explained by an increase in fall precipitation. Small et al. (2006) document that precipitation is generally increasing during the fall but not during the spring, the season when high flows are generally observed. Thus the increase in fall precipitation appears to result in an increase in the low flows while the lack of trends in precipitation in spring explains the lack of widespread trends in the high flows.

With the exception of the study by Villarini et al. (2009), most previous trend studies have employed the hydroclimatic database developed by the U.S. Geological Survey (Slack et al. 1993) which contains basins which are not heavily impacted by regulation by ground and/or surface water withdrawals. Some of the largest anthropogenic influences occur in heavily urbanized regions of the U.S., yet to our knowledge, there are no previous studies which systematically evaluated trends in floods for such basins. Similarly, some of the largest water withdrawals occur in watersheds with very heavy irrigation uses, yet there are no previous studies which systematically evaluated trends in floods for such basins. Thus most previous studies which sought to detect monotonic trends in flood series in the U.S. only focused on flood series which were not heavily influenced by water withdrawals or land use changes. This study takes a different approach by examining flood trends for all USGS flow records in the U.S., regardless of the degree of anthropogenic influence. The primary goal of this study is to determine the locations within the U.S. where very large trends in flood series have occurred and determine the implications of those trends on flood frequency analysis and hydrologic design.

Background, Assumptions, and Methodology

Probability Distribution of Flood Series: Since our goal is to explore trends in annual maximum flood series and their consequence on flood frequency analyses, it is necessary for us to assume a probabilistic model which describes the relationship between the magnitude and frequency of annual maximum flood events. For this purpose, we employ the two parameter lognormal distribution LN2, because among all the probability distributions considered by the Interagency Advisory Committee on Water Data (1982, see Appendix 14), the LN2 and three parameter Log Pearson type III (LP3) distributions performed best in their comparisons and were the only two distributions which did not exhibit significant bias in future flood frequencies. Similarly, among several distributions considered for modeling the frequency of annual maximum floods at 500 basins in the U.S. with records longer than 100 years, Villarini et al (2009) concluded that both the Gamma and LN2 distributions are suitable. Vogel and Wilson (1996) use the larger HCDN dataset along with L-moment diagrams to illustrate that an LN2 distribution gives only a rough approximation to the distribution of annual maximum flood series. They recommend several three parameter distributions such as the generalized extreme value (GEV), LP3 and three parameter lognormal (LN3) distributions. Among all possible two parameter distributions, the LN2 is considered among the best approximations to annual maximum flood series.

We assume that the annual maximum flood series x_t, is observed in each of the following years $t=t_1, t_2, \ldots, t_n$ and that x_t follows an LN2 distribution with quantile function x_p defined as the annual maximum flood with an exceedance probability p or average return period T=1/p. For a stationary flood series, the LN2 quantile function is given by

$$x_p = \exp[\mu_y + z_p \sigma_y] \tag{1}$$

where μ_y and σ_y are the mean and standard deviation of the natural logarithms of x and z_p is the value of a standard normal random variable with exceedance probability p and y=ln(x).

Trend Model for Annual Maximum Floods: As mentioned earlier, there is a rich debate in the literature on (1) whether or not flood series exhibit trends, and (2) what type of trend model provides a good fit to observed flood series. While this study does not seek a definitive answer to either of these questions, we document here that a simple exponential trend model provides an excellent approximation to the relationship, or lack thereof, between annual maximum flood series and time. Consider the exponential trend model:

$$x_t = \exp(\alpha + \beta t + \varepsilon_t) \tag{2}$$

where t is the year in which the annual maximum flood occurs, α and β are model parameters and ε_t are model errors. Taking logarithms one obtains

$$y_t = \ln(x_t) = \alpha + \beta t + \varepsilon_t \tag{3}$$

If estimates of the model parameters α and β, are significantly different from zero, then the regression model provides an estimate of the conditional mean of the natural logarithms of x, which we have defined as μ_y in equation (1). The model residuals in (2) and (3) are only needed to explain the variations of the observations about the regression line, but the regression line itself, provides an estimate of μ_y as a function of time, which we will term $\mu_y(t)$. Combining the fact that $\mu_y(t) = \alpha + \beta t$ with the fact that an ordinary least squares (OLS) estimate of the intercept term is given by $\hat{\alpha} = \overline{y} - \beta\overline{t}$, we obtain the trend model

$$\mu_y(t) = \overline{y} - \hat{\beta}(t - \overline{t}) \tag{4}$$

where $\hat{\beta}$ is an OLS estimate of β, n is the number of years of observations, and:

$$\overline{y} = \frac{1}{n}\sum_{t=1}^{n} \ln(x_t) \qquad \text{and} \qquad \overline{t} = \frac{1}{n}\sum_{t=1}^{n} t = \frac{n+1}{2}$$

This initial study only considers the possibility of a trend in the mean of the annual maximum floods. Future studies should consider the possibility that the variance of the annual maximum floods could change over time due to anthropogenic influences, though such analyses are outside the scope of this study.

A Nonstationary Flood Frequency Model for Floods: The flood frequency model in (1) is a stationary model, because it assumes the moments of y, given by μ_y and σ_y, are fixed. Substitution of nonstationary trend model for $\mu_y(t)$ in (4) for the the fixed value of μ_y in (1) leads to the following nonstationary flood frequency model

$$x_p(t) = \exp\left[\overline{y} + \hat{\beta}\left(t - \frac{n+1}{2}\right) + z_p s_y\right] \tag{5}$$

where s_y is an estimate of the standard deviation of the natural logarithms of the annual maximum floods and the index of time is assumed to be t=1,2,…n. Note that the average value of the years in which flood observations occur can also be rewritten in terms of the first and last year of the flood record t_1, and t_n respectively, which leads to

$$\overline{t} = \frac{1}{n}\sum_{t=t_1}^{t_n} t = \frac{(t_n+1)(t_n - 2t_1 + 2)}{2n} \tag{6}$$

Thus (5) can also be expressed in terms of the first and last year of flood observations as

$$x_p(t) = \exp\left[\overline{y} + \hat{\beta}\left(t - \frac{(t_n+1)(t_n - 2t_1 + 2)}{2n}\right) + z_p s_y\right] \tag{7}$$

Equations (5) and (6) are mathematically equivalent but equation (5) assumes that the index of time in years correspondingto the annual floods is given by t=1,2,…,n whereas, equation (6) is perhaps more useful in practice because the flood series can be indexed by the actual year in which it occurred so that the index of time is $t=t_1, t_2, \dots , t_n$.

Flood Magnification Factors: The primary goal of this study is to explore the impact and significance of observed trends in flood series on the magnitude and frequency of floods. For this purpose, we employ the nonstationary flood frequency model in (5) and (7) to derive what we term the flood magnification factor M defined as a factor by which the current design flood quantile would have to be multiplied by to obtain the magnitude of the flood in some future year. Such a flood magnification factor is defined as

$$M = \frac{x_p(t+\Delta t)}{x_p(t)} \tag{8}$$

where t is some current time period of interest, and Δt is some future planning horizon. Substitution of (5) and (7) into (8) leads to the simple result that

$$M = \exp\left[\hat{\beta}\Delta t\right] \tag{9}$$

So that the increase (decrease) in the design flood quantile over some future period of time Δt, only depends on our estimate of the slope of the flood trends.

Recurrence Reduction Factors: Analogous to the flood magnification factor, one can define a recurrence reduction (RR) as average time between floods in some future year t_f associated with the flood with an average recurrence interval of T_o in some reference year to. If the average recurrence intervals associated with a flood today and in some future year are T_o and T_f, respectively, then their respective exceedance probabilities are given by $p_o=1/T_o$ and $p_f=1/T_f$, respectively. Our concern is what the average recurrence interval associated with the magnitude of the T_o year flood will be in some future year t_f so that RR is is equal to the value of $T_f = 1/ p_f$ corresponding to:

$$x_{p_0}(t_0) = x_{p_f}(t_f) \tag{10}$$

which requires solution of the following expression for $T_f=1/p_f$

$$\exp\left[\overline{y} + \hat{\beta}\left(t_0 - \frac{n+1}{2}\right) + z_{p_0}s_y\right] = \exp\left[\overline{y} + \hat{\beta}\left(t_f - \frac{n+1}{2}\right) + z_{p_f}s_y\right] \tag{11}$$

which leads to

$$T_f = \frac{1}{\Phi\left[z_{p_0} - \frac{\hat{\beta}\left(t_f - t_0\right)}{s_y}\right]} = \frac{1}{\Phi\left[z_{p_0} - \frac{\hat{\beta}\Delta t}{s_y}\right]}$$

where the function Φ( ) is the cumulative density function of a standardized normal variable.

Database

Records of annual maximum instantaneous peak streamflow (AMIPS) were obtained from the United States Geological Survey (USGS) National Water Information System (NWIS). Each AMIPS value was classified as either "regulated" or "non-regulated" based on Peak Streamflow-Qualification Codes provided by USGS (if a value was accompanied by the note "Discharge affected by regulation or diversion" or "Discharge affected to an unknown degree by regulation or diversion," it was placed in the "regulated" category). In an effort to include as many flow records as possible, if a stream gage had

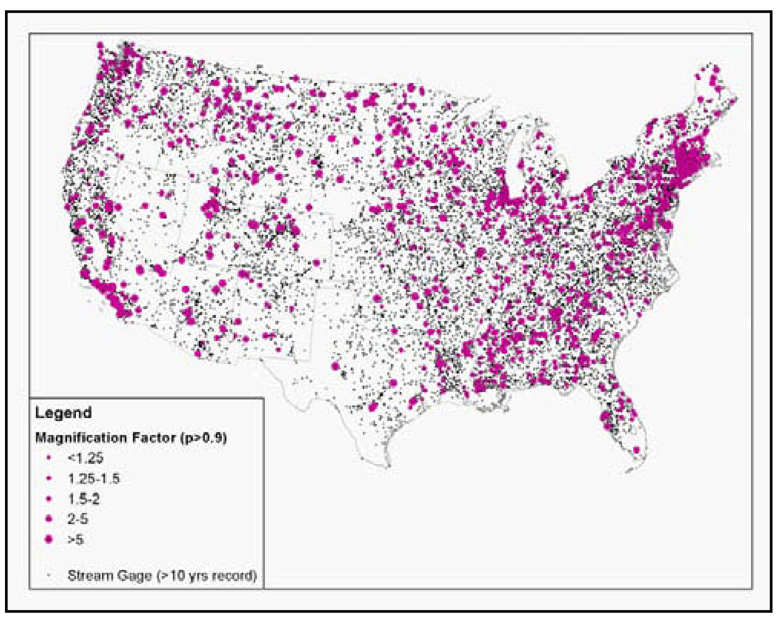

Figure 2. Location of 14,893 stations in the "no regulation" group and the decadal magnification factors associated with the 1,642 (11%) stations which exhibited positive trends.

10 or more AMIPS values in the "regulated" and/or "non-regulated" categories, the gage's record was considered suitable for this study. A gage's record was also given a special classification if the gage was included in the USGS Hydro-Climatic Data Network (HCDN) (see Slack et al. 1993). A total of 14,893 stations were included in the non-regulated group and of those stations, only 1,588 were included in the HCDN dataset. A total of 4,537 stations were included in the regulated group.

Results

The exponential trend model in (4) was fit to all the basins described above. Figure 1 provides an example of the type of results obtained for the Aberjona River basin located just outside Boston MA. Here a significant positive trend was obtained with: $\hat{\beta} = 0.0146$.

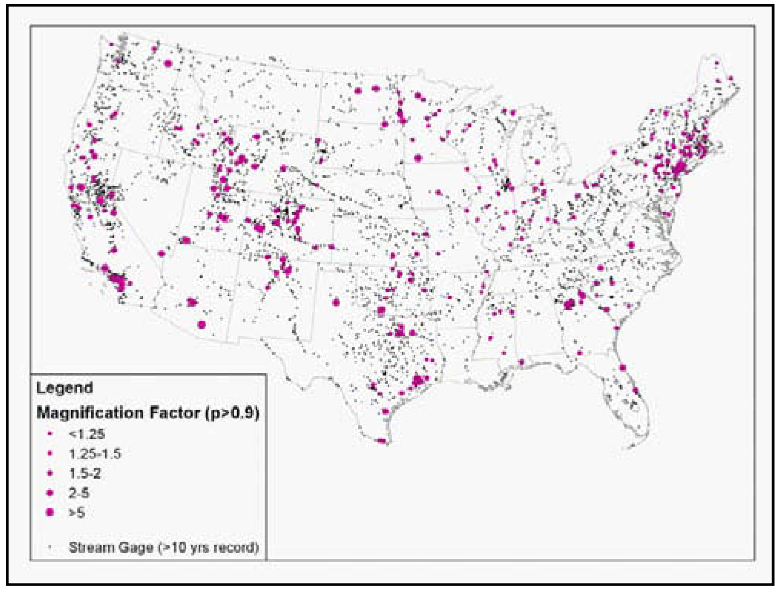

Figure 3. Location of 4,537 stations in the "regulated" group and the decadal magnification factors associated with the 481 (11%) stations which exhibited positive trends.

As already described, there are a broad range of complex statistical issues which make it impossible to be certain that the relation observed in Figure 1 is truly due to a positive exponential trend in the AMIPS. However, common sense indicates that this basin does exhibit increasing flood flows due to the tremendous increases in urbanization which have occurred over the past 70 years (see Ng and Vogel, 2010). To evaluate whether or not a particular site exhibits large positive trends, we only consider stations which exhibited positive trends in streamflow with trend model coefficients which exhibit significance levels of 0.05 or less. Here significance level is computed using a one–sided (since only positive coefficients are explored here) Student's t-test on the slope term in the trend model, and those significance levels are further evaluated to assure that the trend model residuals are independent and normally distributed as is required for such a Students t-test to be reliable.

An automated normality test was implemented to assure that the exponential trend model residuals were normally distributed and to assure that the logarithms of the annual maximum floods were approximately normally distributed and those results are summarized in the appendix. Here we employ the probability plot correlation coefficient (PPCC) test of normality using Blom's plotting position summarized by Vogel (1986) with the critical values computed from the regression equations developed by Heo et al. (2008).

Figure 2 uses very small circles to illustrate the location of the 14,893 stations which were included in the non-regulated group. Of those stations, 1,642 (11%) showed positive trends with p values less than 0.05. Decadal magnification factors are illustrated in Figure 2 using circles whose diameter is proportional to the size of the factor. A decadal magnification factor is defined as $M = \exp\left(\hat{\beta}\Delta t\right) = \exp\left(10\hat{\beta}\right)$. It appears that some of the largest values and largest concentrations of values of decadal magnification factors appear to be occurring in heavily urbanized regions of the U.S. such as in the northeastern coastal corridor, and the urban areas surrounding Los Angeles and Chicago urban. We conclude that future attention should be given to evaluation of flood magnification factors in heavily urbanized regions.

Similarly, Figure 3 illustrates the location of the 4,537 stations which were included in the regulated group along with the decadal magnification factors for the 481 (11%) stations which showed positive trends with $p<0.05$). Similarly Figure 4 illustrates the location of the 1,588 stations which were included in the HCDN group along with the decadal magnification factors for the 208 (13%) stations which showed positive trends ($p<0.05$). Note that in all cases, we obtained more than twice as many positive trends as would be expected by chance, because in all cases we obtained more than twice as many as the 5% expectation associated with our assumed p values. However, since our tests do not account for the spatial cross correlation among the flood series, nor do they account for the possible serial correlation or the possibility of long term persistence, hence we do not conclude that any of the reported trends are statistically significant trends. Rather, we simply claim that these are positive trends which are worth exploring to determine their impact on flood frequency analysis and design.

Figure 5 uses boxplots to illustrate the distribution of the positive decadal magnification factors for the three groups reported earlier in Figures 2-4. The most important result we observe in Figure 5 is that the decadal flood magnification factors for the regulated and nonregulated groups of sites are much higher than for the HCDN sites. This result is extremely important, because it documents how misleading it can be to restrict our attention to the impacts of climate change on streamflow, without considering other sources of changes. Importantly, the sites included in the HCDN dataset which are often assumed to be "pristine" and not effected by development, show relatively small magnification factors even when positive trends were detected. We conclude from Figure 5 that much greater attention should be given to the consequences of flood trends which result from the wide variety of anthropogenic influences which are likely to be causing the large decadal magnification factors for the regulated and nonregulated groups of sites.

Figure 6, illustrates boxplots of the decadal magnification factors for the sites which exhibited negative trends with p values less than 0.05 (again using a one-sided t-test). There does not appear to be a significant difference between the distributions of the decadal magnification factors among the groups.

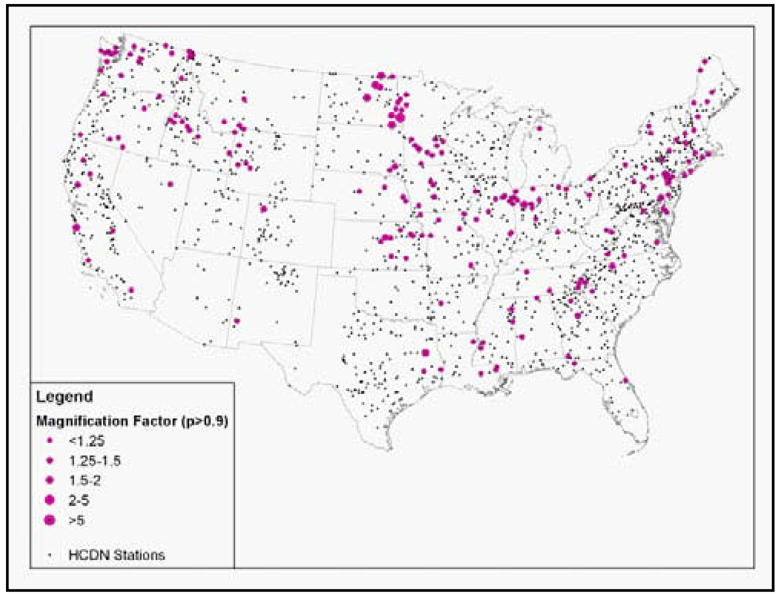

Figure 4. Location of 1,588 stations in the "HCDN" group and the decadal magnification factors associated with the 208 (13%) stations which exhibited positive trends.

Summary and Conclusions

This study has sought to evaluate the impact of trends in flood series on flood frequency analysis and design. Instead of focusing only on the widely used HCDN dataset (Slack et al. 1993) of streamflows not heavily influenced by anthropogenic influences, which has been used in so many previous investigations, we sought a more balanced view of trends in flood series. For that purpose, we employed nearly all the USGS flow records in the U.S. in an effort to ascertain the impact of flood trends which may result from a very broad range of anthropogenic influences including changes in climate, land use, water use, water infrastructure and other forms of flow regulation.

The appendix to this study shows, once again, that a two parameter lognormal model provides a good approximation to the probability distribution of annual maximum instantaneous peak streamflow (x=AMIPS) for most stations. The appendix also demonstrates that the exponential trend model described in equations (2)-(4) provides an excellent approximation to the relationship between the mean of the logarithms of the AMIPS and time. A regression of y=ln(x)=ln(AMIPS) versus time provides an estimate of the conditional mean of y which we termed . This nonstationary model of the mean value of y, conditioned on time, t offers a simple, practical and useful method for modeling the change in the mean of the distribution of flood magnitudes. When combined with the LN2 model, we obtain a simple yet useful nonstationary flood frequency model which should prove useful in planning applications.

Using the nonstationary LN2 flood frequency model, we derive a flood magnification factor which only depends on the slope of the log-linear trend and the interval of time under consideration. Interestingly, for this simple nonstationary LN2 model, flood magnification factors do not appear to depend on the recurrence interval of the flood, so that increases in flood magnitudes resulting from flood trends, appear to be invariant to the magnitude of the flood. This will not be the case if other more complex flood frequency models are employed. Future research should address the role that the form of the flood frequency distribution plays in determining the impact of flood trends on design flood estimates.

Examination of flood records for all regions of the U.S. with the nonstationary flood frequency model introduced here led to the following observations. Stations with significant positive magnification factors appear in all regions of the United States. Three groups of sites considered, non-regulated, regulated, and those stations included in the HCDN dataset. As a group, the stations that were affected by regulation or diversion showed smaller magnification factors than the unregulated stations. Stations included in the HCDN dataset, which were assumed to represent "pristine" conditions, exhibited even smaller positive trends than either of the other two groups. Across all three groups, a similar percentage of sites exhibited significant positive trends, which seems to indicate that flood regulation strategies and development levels within the a given watershed will not affect the chance of that watershed having increasing flood magnitude. However, because

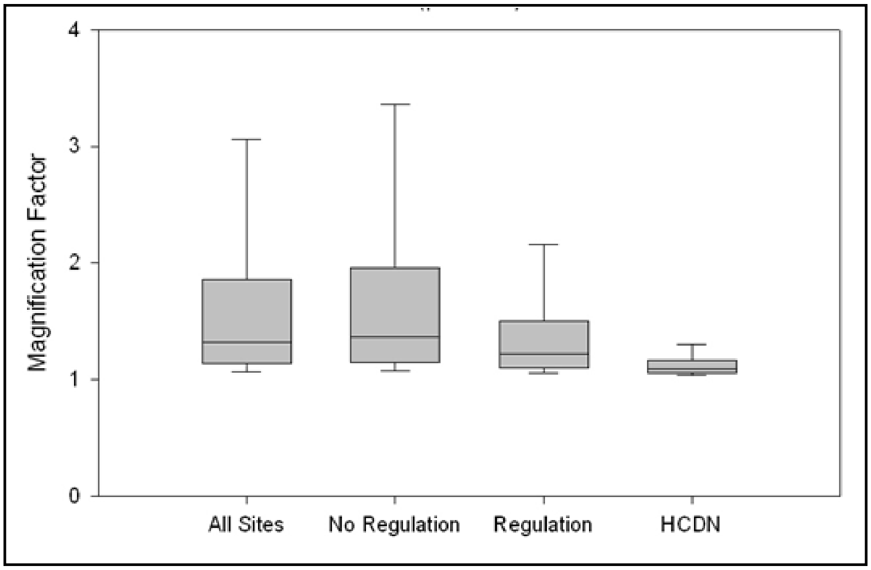

Figure 5. Decadal Magnification Factors the Stations With Positive Trends Shown in Figures 2-4.

unregulated, non-HCDN stations had a much higher range of magnification factors, it does appear that development impacts within a watershed could magnify any naturally caused increases in flood magnitude.

It appears that some of the largest values and largest concentrations of values of decadal magnification factors appear to be occurring in heavily urbanized regions of the U.S. such as in the northeastern coastal corridor, and the urban areas surrounding Los Angeles and Chicago urban. We conclude that future attention should be given to evaluation of flood magnification factors in heavily urbanized regions.

The most important result we observe in Figure 5 is that the decadal flood magnification factors for the regulated and nonregulated groups of sites are much higher than for the HCDN sites. This result is extremely important, because it documents how misleading it can be to restrict our attention to the impacts of climate change on streamflow, without considering other sources of changes. Importantly, the sites included in the HCDN dataset which are often assumed to be "pristine" and not effected by development, show relatively small magnification factors even when positive trends were detected. We conclude from Figure 5 that much greater attention should be given to the consequences of flood trends which result from the wide variety of anthropogenic influences.

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This study has sought to evaluate the impact of trends in flood series on flood frequency analysis and design. Instead of focusing only on the widely used HCDN dataset (Slack et al. 1993) of streamflows not heavily influenced by anthropogenic influences, which has been used in so many previous investigations, we sought a more balanced view of trends in flood series. For that purpose, we employed nearly all the USGS flow records in the U.S. in an effort to ascertain the impact of flood trends which may result from a very broad range of anthropogenic influences including changes in climate, land use,

Significance Level	Stations - No Regulation		Stations - Regulation		Stations - HCDN	
	Total (n=14,893)		Total (n=4,537)		Total (n=1,588)	
	No of Stations Passing	Percent of Stations Passing	No of Stations Passing	Percent of Stations Passing	No of Stations Passing	Percent of Stations Passing
0.005	13,895	93%	3,881	86%	1,424	90%
0.01	13,282	89%	3,603	79%	1,331	84%
0.05	11,485	77%	2,993	66%	1,076	68%
0.1	10,503	71%	2,700	60%	974	61%
	p > 0.9, M > 1 (n=1,642)		**p > 0.9, M > 1 (n=481)**		**p > 0.9, M > 1 (n=208)**	
	No of Stations Passing	Percent of Stations Passing	No of Stations Passing	Percent of Stations Passing	No of Stations Passing	Percent of Stations Passing
0.005	1,526	93%	418	87%	182	88%
0.01	1,461	89%	386	80%	173	82%
0.05	1,256	76%	318	66%	144	69%
0.1	1,128	69%	292	61%	124	60%

Table A-1. Results of lognormal probability plot correlation coefficient (PPCC) hypothesis test results for the three groups of stations at various significance levels.

water use, water infrastructure and other forms of flow regulation.

The appendix to this study shows, once again, that a two parameter lognormal model provides a good approximation to the probability distribution of annual maximum instantaneous peak streamflow (x=AMIPS) for most stations. The appendix also demonstrates that the exponential trend model described in equations (2)-(4) provides an excellent approximation to the relationship between the mean of the logarithms of the AMIPS and time. A regression of y=ln(x)=ln(AMIPS) versus time provides an estimate of the conditional mean of y

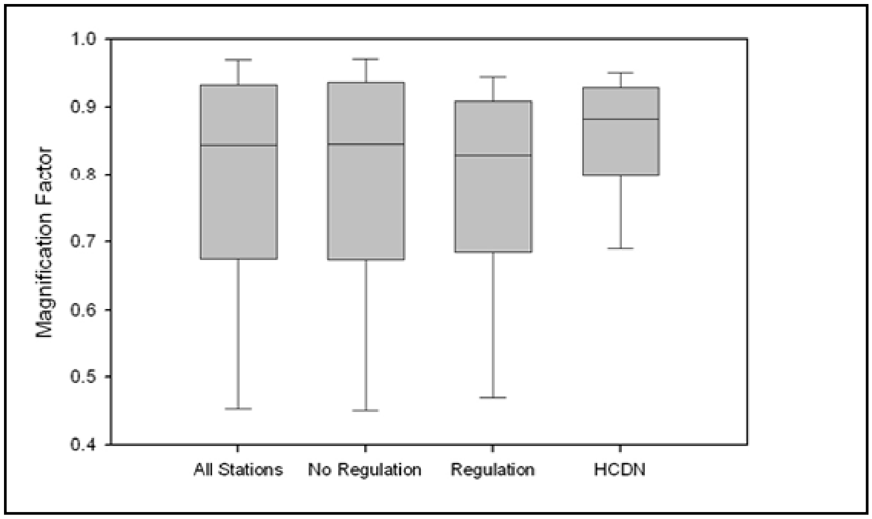

Figure 6. Decadal Magnification Factors the Stations With NegativeTrends

which we termed $\mu_y(t)$. This nonstationary model of the mean value of y, conditioned on time, t offers a simple, practical and useful method for modeling the change in the mean of the distribution of flood magnitudes. When combined with the LN2 model, we obtain a simple yet useful nonstationary flood frequency model which should prove useful in planning applications.

Using the nonstationary LN2 flood frequency model, we derive a flood magnification factor which only depends on the slope of the log-linear trend and the interval of time under consideration. Interestingly, for this simple nonstationary LN2 model, flood magnification factors do not appear to depend on the recurrence interval of the flood, so that increases in flood magnitudes resulting from flood trends, appear to be invariant to the magnitude of the flood. This will not be the case if other more complex flood frequency models are employed. Future research should address the role that the form of the flood frequency distribution plays in determining the impact of flood trends on design flood estimates.

Examination of flood records for all regions of the U.S. with the nonstationary flood frequency model introduced here led to the following observations. Stations with significant positive magnification factors appear in all regions of the United States. Three groups of sites considered, non-regulated, regulated, and those stations included in the HCDN dataset. As a group, the stations that were affected by regulation or diversion showed smaller magnification factors than the unregulated stations. Stations included in the HCDN dataset, which were assumed to represent “pristine” conditions, exhibited even

Significance Level	**Stations - No Regulation**		**Stations - Regulation**		**Stations - HCDN**	
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	No of Stations Passing	Percent of Stations Passing	No of Stations Passing	Percent of Stations Passing	No of Stations Passing	Percent of Stations Passing
0.005	14,041	94%	3,974	88%	1,433	90%
0.01	13,550	91%	3,756	83%	1,359	86%
0.05	11,490	77%	3,159	70%	1,106	70%
0.1	10,958	74%	2,885	64%	1,004	63%
	p > 0.9, M > 1 (n=1,642)		**p > 0.9, M > 1 (n=481)**		**p > 0.9, M > 1 (n=208)**	
	No of Stations Passing	Percent of Stations Passing	No of Stations Passing	Percent of Stations Passing	No of Stations Passing	Percent of Stations Passing
0.005	1,549	94%	436	91%	182	88%
0.01	1,506	92%	406	84%	174	84%
0.05	1,339	82%	361	75%	146	70%
0.1	1,254	76%	326	68%	133	64%

Table A-2. Results of the normal probability plot correlation coefficient (PPCC) test of residual errors for OLS trend regressions fit to individual sites within the three groups of sites at various significance levels.

smaller positive trends than either of the other two groups. Across all three groups, a similar percentage of sites exhibited significant positive trends, which seems to indicate that flood regulation strategies and development levels within the a given watershed will not affect the chance of that watershed having increasing flood magnitude. However, because unregulated, non-HCDN stations had a much higher range of magnification factors, it does appear that development impacts within a watershed could magnify any naturally caused increases in flood magnitude.

It appears that some of the largest values and largest concentrations of values of decadal magnification factors appear to be occurring in heavily urbanized regions of the U.S. such as in the northeastern coastal corridor, and the urban areas surrounding Los Angeles and Chicago urban. We conclude that future attention should be given to evaluation of flood magnification factors in heavily urbanized regions.

The most important result we observe in Figure 5 is that the decadal flood magnification factors for the regulated and nonregulated groups of sites are much higher than for the HCDN sites. This result is extremely important, because it documents how misleading it can be to restrict our attention to the impacts of climate change on streamflow, without considering other sources of changes. Importantly, the sites included in the HCDN dataset which are often assumed to be "pristine" and not effected by development, show relatively small magnification factors even when positive trends were detected. We conclude from Figure 5 that much greater attention should be given to the consequences of flood trends which result from the wide variety of anthropogenic influences

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Appendix

In this section, an automated normality test was implemented to assure that the exponential trend model residuals were normally distributed and to assure that the logarithms of the annual maximum floods were approximately normally distributed. Here we employ the probability plot correlation coefficient (PPCC) test of normality using Blom's plotting position summarized by Vogel (1986) with the critical values of this test statistic computed using the regression equations developed by Heo et al. (2008).

The validity of the assumption of lognormality was tested for the three groups of stations at various levels of significance. The results of the lognormal PPCC test is summarized in Table A-1. These results indicate that a lognormal distribution provides a good approximation to the distribution of flood magnitudes, with roughly 90% of sites in any of the three groups passing a PPCC test using a 0.005 significance level. Additionally, the subset of stations with positive trends exhibits approximately the same goodness-of-fit associated with the lognormal distribution as the greater population. This seems to indicate that stations with positive trends are not outliers to which the assumption of lognormality is not applicable.

The validity of the OLS regression model was also tested for the three groups of stations at various significance levels. The results of the PPCC tests of the normality of the OLS regression residual errors is summarized in Table A-2. The results indicate that OLS regression is valid for a majority of stations; once again about 90% of sites pass a PPCC test with a 0.005 significance level in any of the three groups. The subset of stations with positive trends pass the PPCC test at about the same rate as the larger population. In other words, the stations with positive trends are as well described by OLS regression as sites with no trends or negative trends.

Biography

Richard Vogel is a professor of civil and environmental engineering and has been at Tufts University since 1984. His primary expertise is in the areas of water resource engineering with emphasis on hydrologic, hydraulic and statistical methods for analyzing environmental and water resource systems. His current research program focuses upon the areas of hydrologic and environmental statistics, water allocation, regional hydrology, regional water assessment, flood and drought management, climate change impacts, natural hazards as well as watershed modeling and management. His consulting experiences have included water resource assessment, flood frequency analysis, water allocation, hydropower feasibility analyses, and water supply investigations for several major cities, floodplain delineations, stormwater management modeling, dam safety analyses, ice jam control and climate change impact assessments. He is currently contributing editor of the ASCE Journal of Water Resources Planning and Management. He was awarded the 1995 Walter L. Huber Prize in Civil Engineering and the 2009 Julian Hinds Award. He has published over 85 refereed journal articles which have received over 1300 citations with an h-index of 22. He is currently the director of the graduate program in Water: Systems, Science and Society.

Future Climate and Hydrologic Variability: Interpreting Climate Model Information

Model Ensembles to Distributions

Levi Brekke, U.S. Bureau of Reclamation

NOTE: *This is an edited transcript of the author's remarks at the workshop and not a submitted paper. To view this author's presentation, visit http://www.cwi.colostate.edu/NonstationarityWorkshop/SpeakerNotes/Thursday Morning/Brekke.pdf on the web.*

Abstract

The process of incorporating climate change information into long-term water resources planning requires decisions on (1) which climate projections to use and (2) how to use them when developing planning assumptions that reflect future climate. Broadly speaking, planning assumptions relate to portrayal of water supplies, water demands and operations constraints in water resources management studies, or portrayal of hydrologic hazard possibilities in infrastructure safety and flood risk reduction studies.

This presentation introduces several issues and questions that complicate the two decisions listed above. On the first decision, should all projections be regarded as eligible for planning use, or can we rationalize throwing? Does our sense of climate projection uncertainty change if we go ahead and do so? On the second decision, after we've decided which projections to retain, what aspects of projected climate do we want to reflect into planning assumptions? Do we wish to map the time-developing aspects of the climate projections to associated projections of hydrology (e.g., time-changing probabilities of droughts or surplus occurrence)? Or do we only wish to only sample the projections for changes in period-climate (e.g., 30-year climate norms)? The latter path has been demonstrated many times in research literature and in recent planning practice. However, the matter of low-frequency variability affects interpretation of projected changes in 30-year climate: are these sampled changes "climate change" or "a blend of climate change and natural variability"? Answers to these questions have implications for characterizing hydrologic and water management impacts, and associated adaptation needs.

Introduction

I imagine a lot of folks are wrestling with how to relate climate projection information to hydrologic analysis. That provides context for this talk and I'd like to introduce two broad questions that we frequently hear.

- Should we focus on some projections and throw out others?
- Does this choice affect portrayal of climate change uncertainty?

People are well aware that there are many global climate projections out there from many different climate models and different emissions scenarios. Some are even aware that they start with different initial conditions called run numbers for modeling emissions in combo.

So given awareness of this wealth of climate projection information, and given the will to somehow relate it to your hydrologic analysis, a frequently asked question is whether we should focus on some projections and throw out others. This is often asked with the hope of reducing projection uncertainty used in the hydrologic analysis.

There have been a number of studies in the published literature in recent years addressing this subject. One take, which is also my take that others may disagree with, is that it is pretty easy to rank models. It's hard to rank emissions, but you can rank models. And it's easy to throw out a model, based on whichever range you can come up with. However, it's not so clear to demonstrate that it matters when you consider model ranking when assessing projection uncertainty (Slide 3[1]). There are reasons for that, namely uncertainties introduced by the greenhouse gas emissions scenarios and also by the initial condition possibilities at the start of future climate simulations. I'll dive into the latter issue later in the talk.

However, on the matter of ranking climate models and using results to affect assessments of projection uncertainty, the case isn't closed. This is still an adolescent area of research. For now, you can easily rationalize keeping consideration for all global projections, or you can rationalize throwing some out. I don't know that there's a right or wrong answer at this time. It's not necessarily a palatable response to that question, but I think it's a fair response.

[1] http://www.cwi.colostate.edu/NonstationarityWorkshop/SpeakerNotes/Thursday Morning/Brekke.pdf

So let's say you proceed with your study, and you want to decide on which aspects of climate projections you wish to relate to your hydrologic analysis. There are a number of questions:

- Use which projection aspects? (e.g., variables, statistical description of these variables)
- Time-evolving? (e.g., moving statistics, changing frequency of drought or surplus potential)
- Or do we only wish to simply reflect change in period-climate (e.g., 30-year climate norms, which periods)? Is it really that simple?

One approach is to just adopt a time-evolving, transient projection view and map the climate projections to hydrologic projections and operations projections. There have been studies that have demonstrated this technique in the literature. They feature moving climate and hydroclimate statistics. They inherit a climate projection's protrayed developments in the frequency of drought and surplus periods.

To illustrate a time-developing or time-evolving view using a climate projection ensemble, consider an ensemble of climate projections over Vancouver, British Columbia (Slide 5[1]). The upper panel shows an ensemble of annual temperature projections, and the bottom panel shows a corresponding ensemble of precipitation projections.The time-evolving ensemble view invites you to track the ensemble-consensus condition through time and maybe emphasizes the ensemble central tendency through time. In this sense, you're being invited to interpret change as it develops; i.e., a time-developing view. The rub with this is that you're inheriting all these projection variability aspects that are questionable; there's a big trust factor there.

In response to the question of time-developing or period-change approach, maybe you respond by saying that you don't want to trust the variability from the projections. Therefore, you opt for the period-change approach and proceed by sampling the projections –for, say, a change in 30-year climate in order to define climate change possibilities for your study. Those changes in mean climate would then be imposed on your historical sense of climate variability, and the combinations would serve as the climate variability portrayal in your analysis.

The vast majority of impact studies you'll find in the literature adopt this kind of a view. Compared to time evolving, you might think of this as a simple approach. What I hope to introduce are some thoughts today that maybe this interpretation isn't that simple, particularly when you get to precipitation projections and the matter of interpreting sampled changes in 30-year mean precipitation. To illustrate, consider the common goal of characterizing hydrologic impacts under climate change defined as a change in 30-year mean climate. These definitions are drawn from a collection of projections, each providing a unique climate change increment. You're going to translate period change in climate into period change in hydrology, and then use that change information to adjust the inflow variability in your operations analysis.

To illustrate, consider a simple system, the Trinity Reservoir and inflow to Trinity Reservoir (Slide 8[1]). On the left panel, what you're seeing a historical periods of annual inflow variability at Trinity Reservoir. Conceptually, I'm showing results from a period change analysis. Let's say we had a defined climate change increment in the hydrologic analysis and it resulted in a reduction of mean annual Trinity Reservoir flow of 10%. And then we take that 10% and we adjust the historical observed Trinity inflow down 10%.

The resultant historical and "climate change" inflow datasets are summarized on the right panel. Boxplots show the assumed variability of annual inflow for each climate condition. The blue boxplot is for historical and the red box plot is historical adjusted for the increment of climate change. We then proceed to our operations analysis, comparing operations results under both inflow sequences, and compare results to tell our impact story.

This example involves only a single climate change increment. We can always extend this approach to consider multiple climate change increments. Consider the earlier slide showing time evolving climate projections over example with Vancouver (Slide 9[1]). I've highlighted two 30-year periods used to assess climate change increments using green rectangles. The historical period is from 1971 to 2000, while future period is from 2041 to 2070. We compute change in 30-year mean temperature and precipitation for all 112 projections. Doing this allows us to portray a rich set of climate change information. However, we're assuming that each projection-specific change is a climate change possibility, and that's a matter that invites careful consideration.

To recap, in a period-change application we adopt climate change metrics, look at an ensemble of change possibilities, possibly for the purposes of identifying a few climate change scenarios for planning (maybe bracketing scenarios), we select projections that express "climate changes" that bracket the spread of changes. This is all predicated on being able to interpret that the computed changes as "possible climate change" (Slide 10[1]). At issue is whether these computed changes might actually be a blend of climate change and low-frequency or multidecadal variability.

Given the possibility of the latter, this raises questions about how we impose these change increments on a historical envelope of variability, like we did with the Trinity example. The historical envelope of variability also has low-frequency variability embedded in it. To elaborate on this matter of low-frequency variability and to characterize its presence in the regional climate projections over the western U.S., I'm going to share some results over eight basins in the western U.S.

We start with an ensemble of 112 CMIP3 bias-corrected and spatially downscaled precipitation projections[2]. The bias-correction means that the raw GCM data have been adjusted so that they have period statistics that are common to an historical reference during the late 20th Century. The bias-correction permits us to assess relative change aspects in the projections in the context of our historical observations.

We next look at eight western U.S. basins. For each of these eight basins, I'm computing 30-year period climates in each projection during five non-overlapping periods: the first 30 years of that 150 years, from1950 to 1979, and so forth and to the last 30 years, 2070-2099. I'm labeling the periods 1 through 5.

To assess low-frequency variability presence in the projections, I'm using two methods (Slide 11[1]). One way is to look at the period-change with moving period pairs, meaning period (2) minus period (1), then period (3) minus period (2), and so forth. And in the other way, I'll fix the first period, and compute changes: period (2) minus period (1), then period (3) minus period (1) and so forth. The purpose in both cases is to look at how stable the climate change is in time. If the sign changes in time progression, that suggests presence of low-frequency variability in the given projection.

We first consider case one involving climate change assessment with moving pairs: is the change sign stable through time? An example of unstable change sign would be, for example, a case where the sign of precipitation change is negative with periods of (2)-(1) but then positive when it's (3)-(2). That's a relatively common situation in the projections; the more uncommon situation is unstable change sign when the historical period is fixed.

To illustrate, consider Trinity Reservoir (Slide 14[1]). It shows the ensemble of climate projections over the Trinity Reservoir Basin. What you're seeing are 112 traces for 112 projections. Each trace represents an annually moving 30-year mean, precipitation in this case. So the first plot point of any trace is situated on 1979 and represents 30-year mean from 1950 to 1979. The next point is from 1951 to 1980, and so forth. So in other words, we're just annually indexing the 30-year mean and tracking the mean through time.

I'm just highlighting the ensemble of points at five times the data, always at the end of the five periods we're interested in (periods 1-5). This means I've focused on points at 1979, 2009, 2039, 2069, and 2099. I also show lines connecting points from time stage to time stage to indicate how each projection's expression of climate evolves through time. Each set expresses spread of period climate possibility at that point in time.

If I examine the stability of signs using the first approach (moving period pairs), there's an instability in sign of change For example, one projection might show that sign of change from (3) to (2) is positive but from (4) to (3) it switches to negative. Nine out of 10 projections express precipitation change instability like this. About half the projections express that type of sign instability.

The next slide elaborates on that latter thought (Slide 15[1]) and illustrates four examples where sign change is unstable in the second way of assessment. For example, consider the green line. The change in period (2) minus period (1) looks like roughly minus 8 percent, but then it's flipped to plus 10 percent for period (3) minus period (1), stays positive thereafter. The blue projection starts positive, increase to plus 18, then dropped to minus eight, and then went positive again.

So about half of the projections express this type of sign instability which is interpreted here as some expression of low-frequency regional climate variation in the projections. Is this only a Trinity thing? No, actually the results were very consistent across the eight basins we looked at (Slide 16[1]). For the moving pairs cases, it went anywhere from eight to nine out of 10 that's in that type of low-frequency variation. For the fixed historical case, about half of the projections expressed low-frequency variation in most basins.

So given that the projections express low-frequency variations in regional climate (precipitation), questions might be asked on why this is the case? It might help to understand how global climate projections are constructed in the CMIP exercise as of now. A CMIP 3 projection is using three climate simulations. First, you have your pre-industrial simulation

[2] http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/

(Slide 17[1]), where the atmosphere and the climate forces are inferred by paleo evidence and paradigm assumptions. So the climate modeling group does this simulation, sometime referred to as a preindustrial climate spin-up simulation. The end of that simulation serves as the initial condition for the 20th Century simulation with atmospheric composition and climate forcings informed by observations from the 20th Century. As for the initial condition for simulation year 1900, it is not heavily constrained by observation. For example, we don't have a lot of information on what the distributed heat content in the oceans was in 1900. So that being the case, the year 1900 climate state is left unconstrained and happens to be inconsistent across the CMIP3 projections.

So then we do our 20th century simulation (Slide 18[1]) and the 20th century simulation ends in a year indexed as 1999. This serves as the initial condition for our 21st century simulation (Slide 19[1]). Again, the year 2000 climate state is not constrained heavily to match the distributed conditions in the climate system in the year 2000. So, the initial conditions for the 21st century simulation are again permitted to be inconsistent.

In addition to differences in initial conditions, CMIP 3 conditions are also generated by a collection of global climate models that express internal variability (natural climte variability) in different ways (Slide 20[1]). Some express little low-frequency variability, others express a lot.

The two issues of initial conditions and climate model tendencies on simulation of internal variability interact to affect regional conditions. The question is how significant these interactions are when we're interpreting our regional period-change assessment as climate change possibilities (back on the Trinity or Vancouver examples). Studies looking at this question from a global view suggest that the time-shadow of initial conditions may not be that significant when assessing future impacts. When asking this qeustion from a regional view, the time shadow can be considerably longer. For example, a study by Hawkins and Sutton (2009) focused on attributing sources of future climate projection uncertainty to internal variability, climate model choice and emission scenario choice, and to track that attribution through time. For the global view, the time shadow of significant attribution to internal variability and initial conditions was not that long. But for a regional view over the British Isles, which isn't that small of an area, the time shadow lasted several decades, suggesting that internal variability and initial conditions can be a significant source of uncertainty in interpreting projections for regional climate change information.

So this is something to be aware of when you're trying to simply compute change in 30-year means and interpret these as climate changes for planning purposes. So for period-change studies, what are some hanging issues or questions? (Slide 21[1])

- Interpreting the "precipitation climate changes" we sample from projections
- How can we be certain we're not double counting variability and mischaracterizing adaptation need?
- Is the time-evolving view a remedy?

On interpreting the precipitation climate changes, we're sampling change possibilities from projections. What's the best way to interpret what we sample?

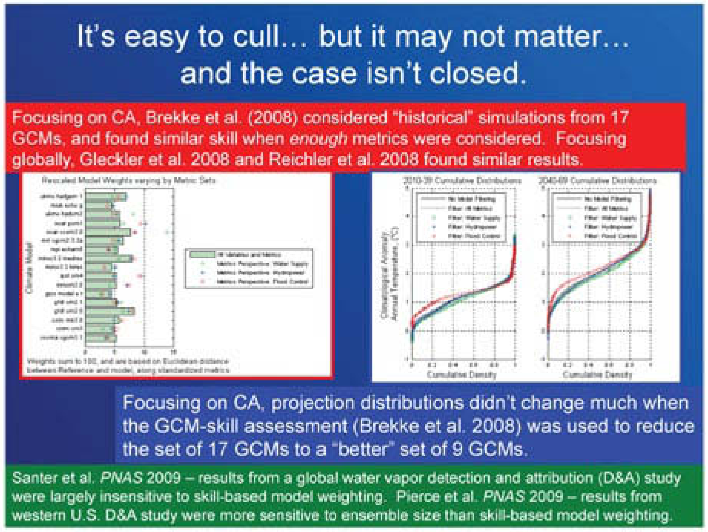
On double-counting variability, we discussed low-frequency variability and unstable climate change through time in the projections. Note that I didn't discuss the presence of drifting projections in that ensemble, which is another challenge to interpreting projection information. How can we be certain that we're not double-counting or misapplying our climate change definition with our historical envelope of variability in the period change aspects and, in doing so, mischaracterizing adaptation need?

The last item recognizes that these challenges apply for period-change applications, where we have to define and diagnose climate change from projection information. What if we adopted a time-evolving view? Maybe we avoid the responsibility of diagnosing climate change, but then you need to trust the projected variability coming from the projection, and that has its own rubs.

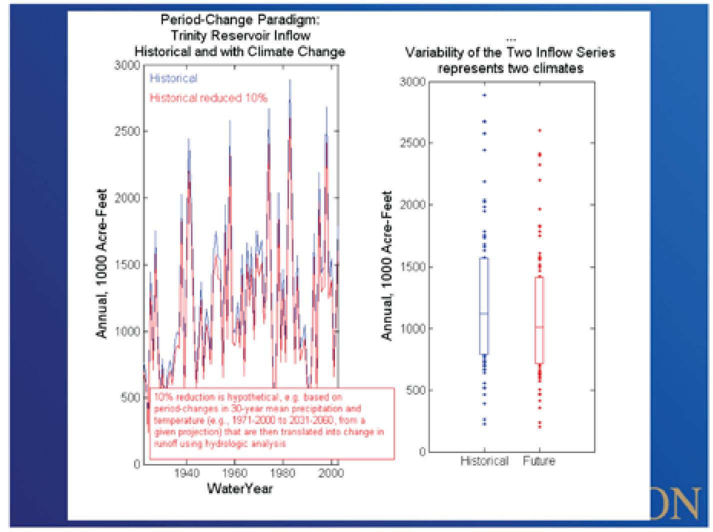
Biography

Levi Brekke works at Reclamation's Technical Service Center in Denver. His work focuses on hydrology and reservoir systems studies, technical team coordination, and conducting research on climate change implications for water resources management. Levi's education includes a B.S.E. in Civil Engineering (The University of Iowa), M.S. in Environmental Science and Engineering (Stanford University), and Ph.D. in Water Resources Engineering (University of California Berkeley).

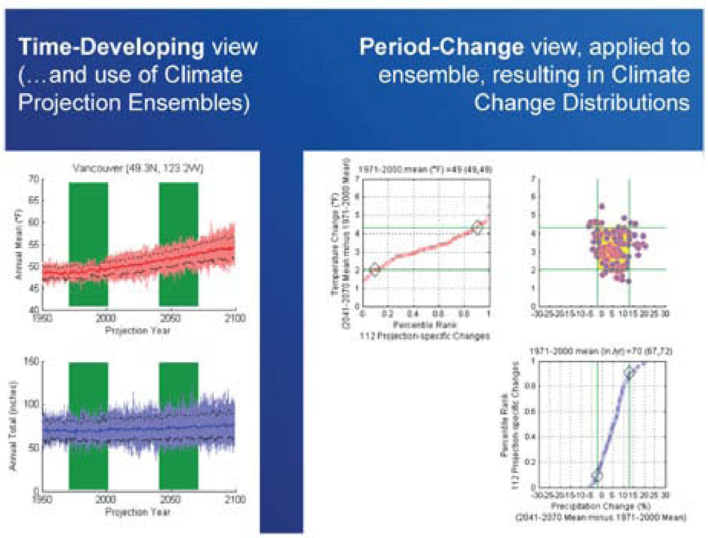
The following slides are extracts from Levi Brekke's full presentation found on the web at: http://www.cwi.colostate.edu/NonstationarityWorkshop/SpeakerNotes/Thursday Morning/Brekke.pdf



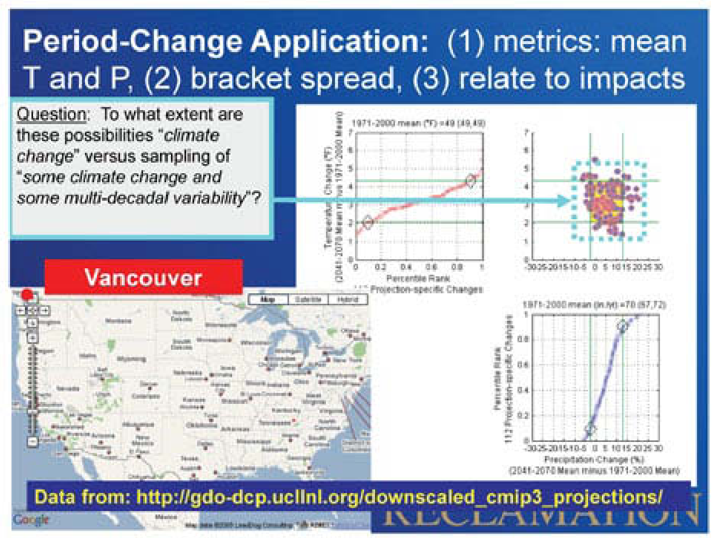
Slide 3



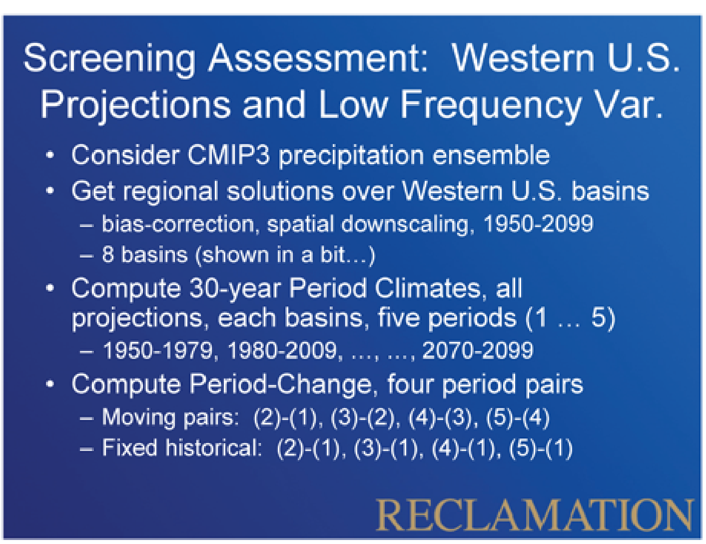
Slide 8



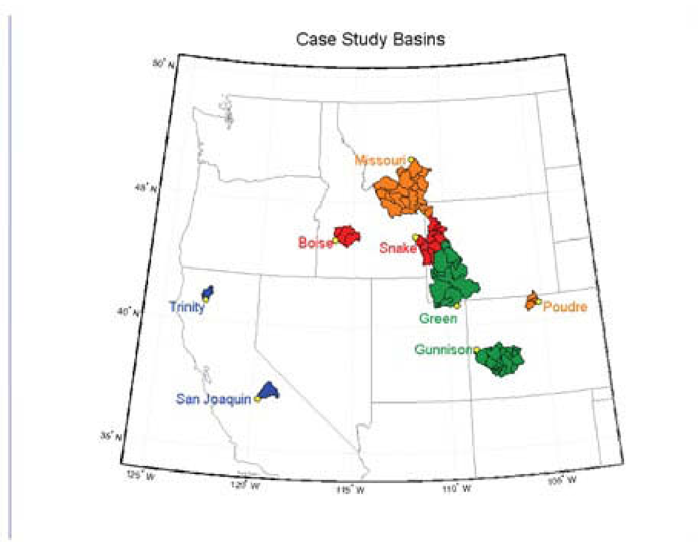
Slide 9



Slide 10



Slide 11

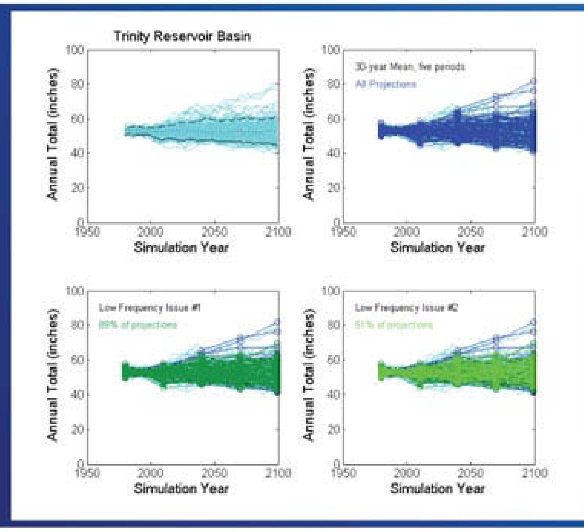


Slide 12

Screening Assessment (cont.)

- Examine for low frequency variations – is the sign of change through time?
- Define Case 1
  - moving pairs, does sign change?
    - e.g., (2)-(1) is neg, but (3)-(2) is pos…
- Define Case 2
  - fixed historical, does sign change?
    - e.g., (2)-(1) is neg, but (3)-(1) is pos…

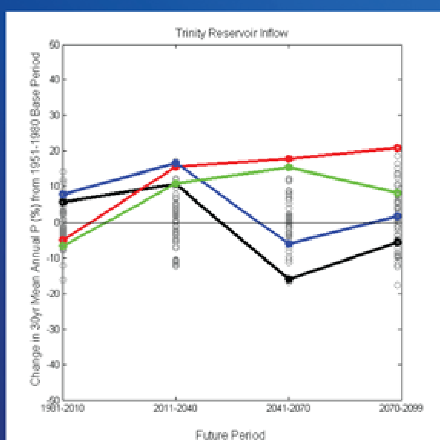
Slide 13



Slide 14

Trinity:

four example projections showing Case 2 (i.e. period-change sign flip relative to fixed 1950-1979 reference period)



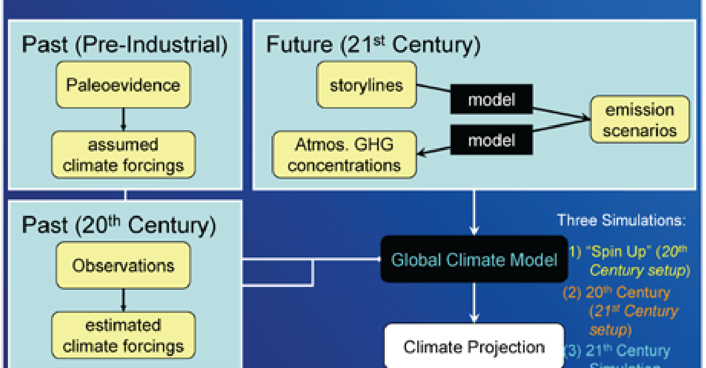
Slide 15

Other basins, Precipitation…

Basin	Moving Pairs case… % showing sign chng.	Fixed Historical… % showing sign chng.
Boise (ID)	80%	50%
Green (WY)	87%	52%
Gunnison (CO)	88%	58%
Missouri (MT)	85%	52%
Poudre (CO)	79%	42%
San Joaquin (CA)	91%	49%
Snake (WY)	78%	47%
Trinity (CA)	89%	51%

Slide 16

Making a CMIP3 projection

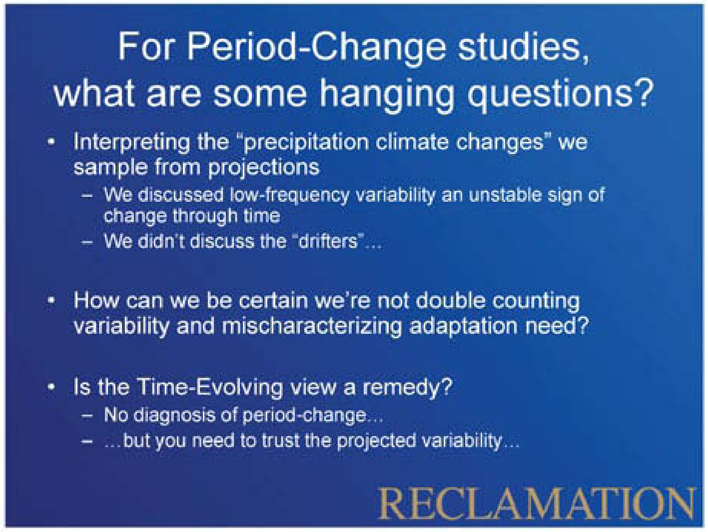


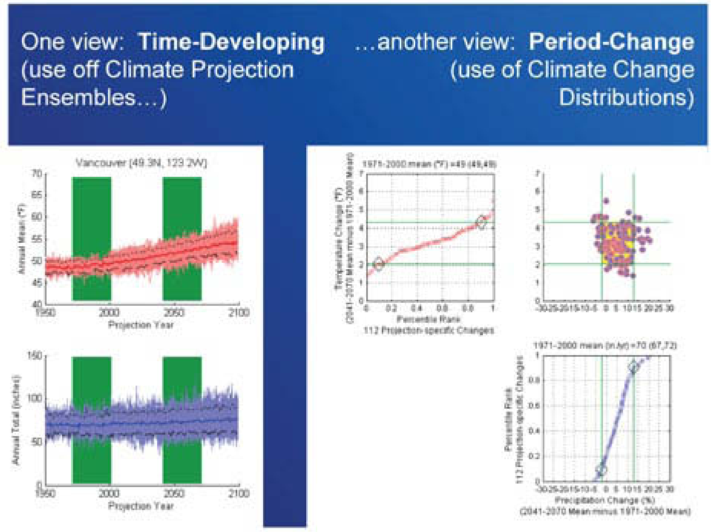
Slide 19

Issues affecting Regional Period-Change in Global CMIP3 Projections

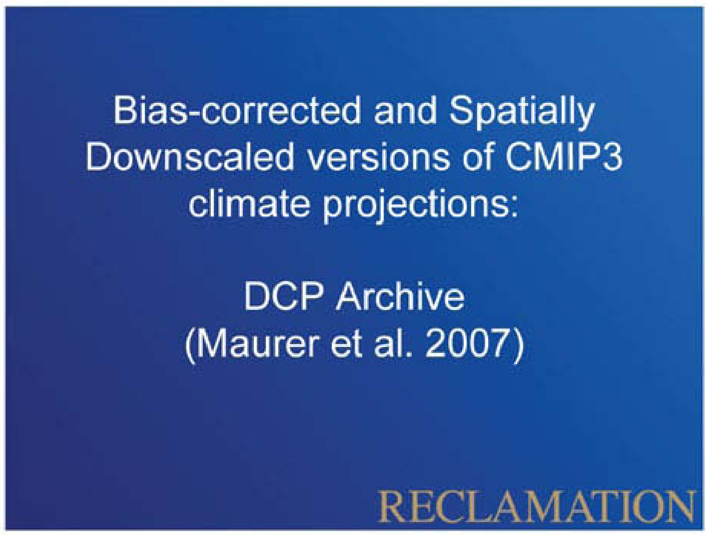
- CMIP3 projections have different initial conditions
  - Previous slide…
- GCMs express different internal variability
  - Some express no little frequency variability, others a lot
- These two conditions interact, cast time-shadow on interpreting regional projection uncertainty
  - Can last decades, see Hawkins and Sutton (2009)

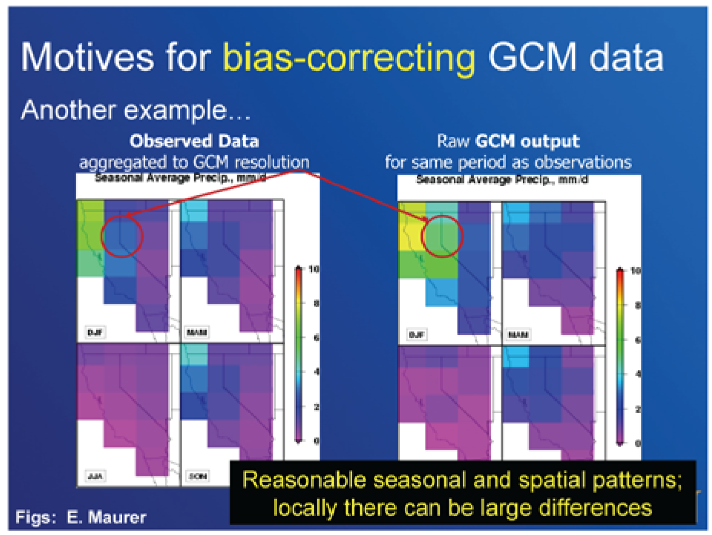
Slide 20

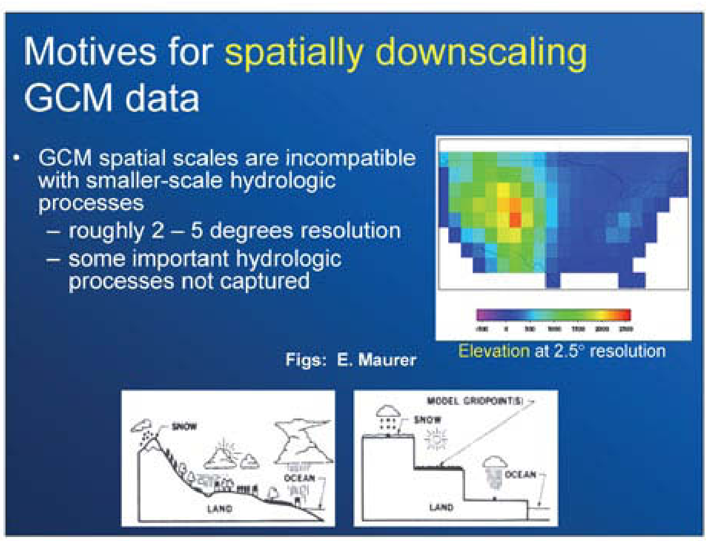

For Period-Change studies, what are some hanging questions?
Interpreting the "precipitation climate changes" we sample from projections
We discussed low-frequency variability an unstable sign of change through time
We didn't discuss the "drifters"…
How can we be certain we're not double counting variability and mischaracterizing adaptation need?
Is the Time-Evolving view a remedy?
No diagnosis of period-change…
…but you need to trust the projected variability…
RECLAMATION


One view: Time-Developing (use off Climate Projection Ensembles…)
…another view: Period-Change (use of Climate Change Distributions)
Vancouver (49.3N, 123.2W)
Projection Year
Projection Year

Slide 21


Bias-corrected and Spatially Downscaled versions of CMIP3 climate projections:
DCP Archive
(Maurer et al. 2007)
RECLAMATION


Motives for bias-correcting GCM data
Another example…
Observed Data
aggregated to GCM resolution
Raw GCM output
for same period as observations
Seasonal Average Precip., mm/d
Seasonal Average Precip., mm/d
Reasonable seasonal and spatial patterns; locally there can be large differences
Figs: E. Maurer


Motives for spatially downscaling GCM data
GCM spatial scales are incompatible with smaller-scale hydrologic processes
– roughly 2 – 5 degrees resolution
– some important hydrologic processes not captured
Figs: E. Maurer
Elevation at 2.5° resolution
SNOW
OCEAN
LAND
MODEL GRIDPOINT(S)
SNOW
OCEAN
LAND

Climate Change, Atmospheric Rivers, and Floods in California: A Multi-Model Ensemble Analysis of Projections of Storm Frequency and Magnitude Changes

Michael Dettinger, U.S. Geological Survey, Scripps Institution of Oceanography

Abstract

Several recent studies have shown the important role that "atmospheric rivers" (ARs) of concentrated near-surface water-vapor transport above the Pacific Ocean play in historic storms and floods in the West Coast states. By delivering large masses of warm, moist air (sometimes directly from the Tropics), ARs establish conditions for the kinds of high snowlines and copious rainfall that have caused the largest historical storms in California, Oregon, and Washington. In many California rivers, essentially all major historical floods have been associated with AR conditions. Thus the future of these storms is likely to have an important influence on nonstationarities of flood frequencies and magnitudes in the face of projected 21st century climate changes.

As a concrete example of the kinds of storm changes that may underlie future flood-frequency changes, the occurrence of such storms in historical observations and in a 7-model ensemble of historical-climate and projected future-climate simulations has been evaluated. Under an A2 greenhouse-gas emissions scenario (with emissions accelerating throughout the 21st century), average AR statistics do not change much in most climate models; however, extremes change notably. Years with many AR episodes increase, ARs with higher-than-historical water-vapor transport rates increase, and AR storm-temperatures increase. Furthermore, the peak season within which most ARs occur is commonly projected to lengthen, extending the flood-hazard season. All of these tendencies could increase opportunities for both more frequent and more severe floods in California under projected climate changes.

Introduction

Major floods are a recurring theme in California's climatology and hydrology, and have a long history of being an important cause of death and destruction in California (Kelley, 1998). Even today, California's aging water supply and flood protection infrastructure, including more than a thousand kilometers of levees, is being challenged by punishing floods and increased standards for urban flood protection. Many Californians face unacceptable risks from flooding, both from where they live and work and from where they derive water supplies. In response to the risks and conflicts posed by flooding, the California Department of Water Resources Water Plan Updates in both 2005 and 2009 strongly recommend that water supply management, land use development, and flood management in the State be much more fully integrated (DWR 2005, 2009). The Delta Vision Task Force has identified improvements in floodplain and flood emergency management among its key recommendations for the future of California's Delta (Delta Vision Task Force, 2008). Perhaps most convincingly, the people of California passed Propositions 1E and 84 in 2006 to fund bonds intended to provide over $4.5 billion specifically for flood management programs in the State.

Although uncertainties abound, a significant part of this focus has been motivated by the risks that flood may occur more frequently or become more extreme with climate changes due to increasing greenhouse gas concentrations in the global atmosphere. Current climate change projections for 21st century California uniformly include warming by at least a couple of degrees, and although great uncertainties remain about future changes in long-term average precipitation rates in California (e.g., Dettinger 2005; Cayan et al. 2008), it is generally expected that extreme precipitation episodes may become more extreme as the climate changes (Trenberth, 1999; Cayan et al., 2009). As a step towards better understanding

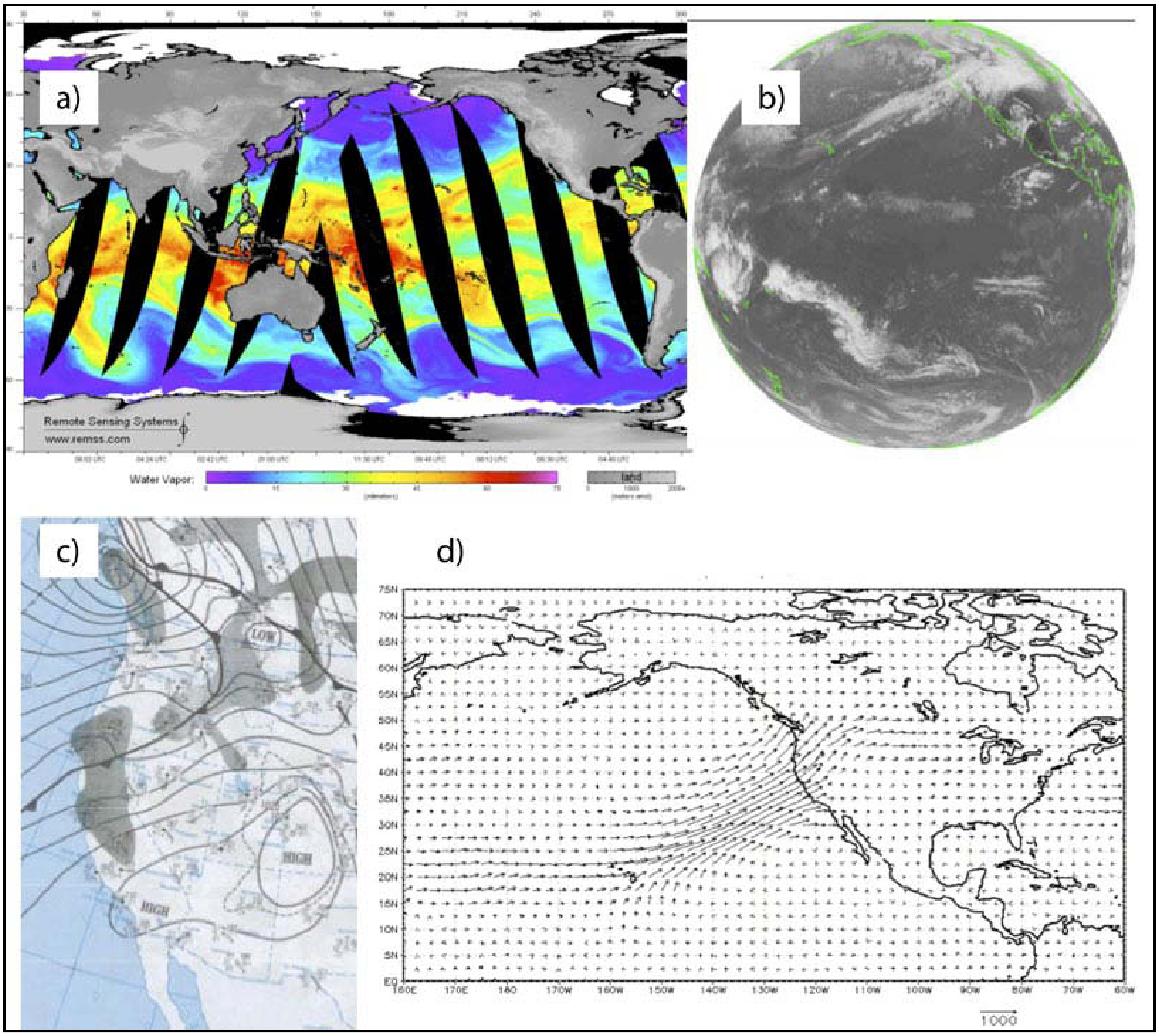


Figure 1. SSM/I integrated water vapor imagery from GMT morning on 2 January 1997 (panel a; warm colors for more vapor, cool colors for less), infrared weather-satellite imagery of the Pacific Ocean basin (GOES-West) from 1800 hours GMT on 1 January 1997 (panel b; light colors are cloud bands, coasts indicated in green), corresponding daily weather map (c) and vertically integrated water-vapor transport directions and relative rates (d) from NCAR-NCEP Reanalysis fields; arrow at bottom indicates length of a 1000 kg/m/s vapor-transport vector.

of the risks and as an example of analysis of frequency changes in a specific storm and flood mechanism as a way of understanding likely overall flood frequency changes, this paper summarizes a preliminary analysis of the 21st century future of a particularly dangerous subset of flood-generating storms — the pineapple-express or atmospheric-river storms — from seven current climate models.

Characteristics of Atmospheric-River Storms

Although warming alone may be expected to alter flood regimes in many snow-fed settings (e.g., Dettinger et al., 2009), changes in California's storm types, frequencies, or magnitudes may provide more direct and pervasive opportunities for change. Historically, probably the most dangerous storms in California have been warm and wet storms that strike in winter, producing intense rains over large areas and unleashing many of the State's largest floods. The most commonly recognized of these storms have been described as "pineapple express" storms because of the way that they are observed (in weather satellite and other imagery, e.g., Figure 1) to draw warm, moist air from the tropics near Hawaii northeastward into California (Weaver 1962, Dettinger 2004). More recently, studies have highlighted the fact that "pineapple express" storms in California are just one version of a more common feature of the mid-latitude atmosphere. It has been estimated that about 90% of all the water vapor transported towards the poles across the midlatitudes is transported within narrow, intense filamentary bands of moist air, called atmospheric rivers (ARs, Zhu and Newell 1998), that together typically span less than about 10% of the Earth's circumference at any given latitude. Ralph et al (2006) recently noted that all "declared"

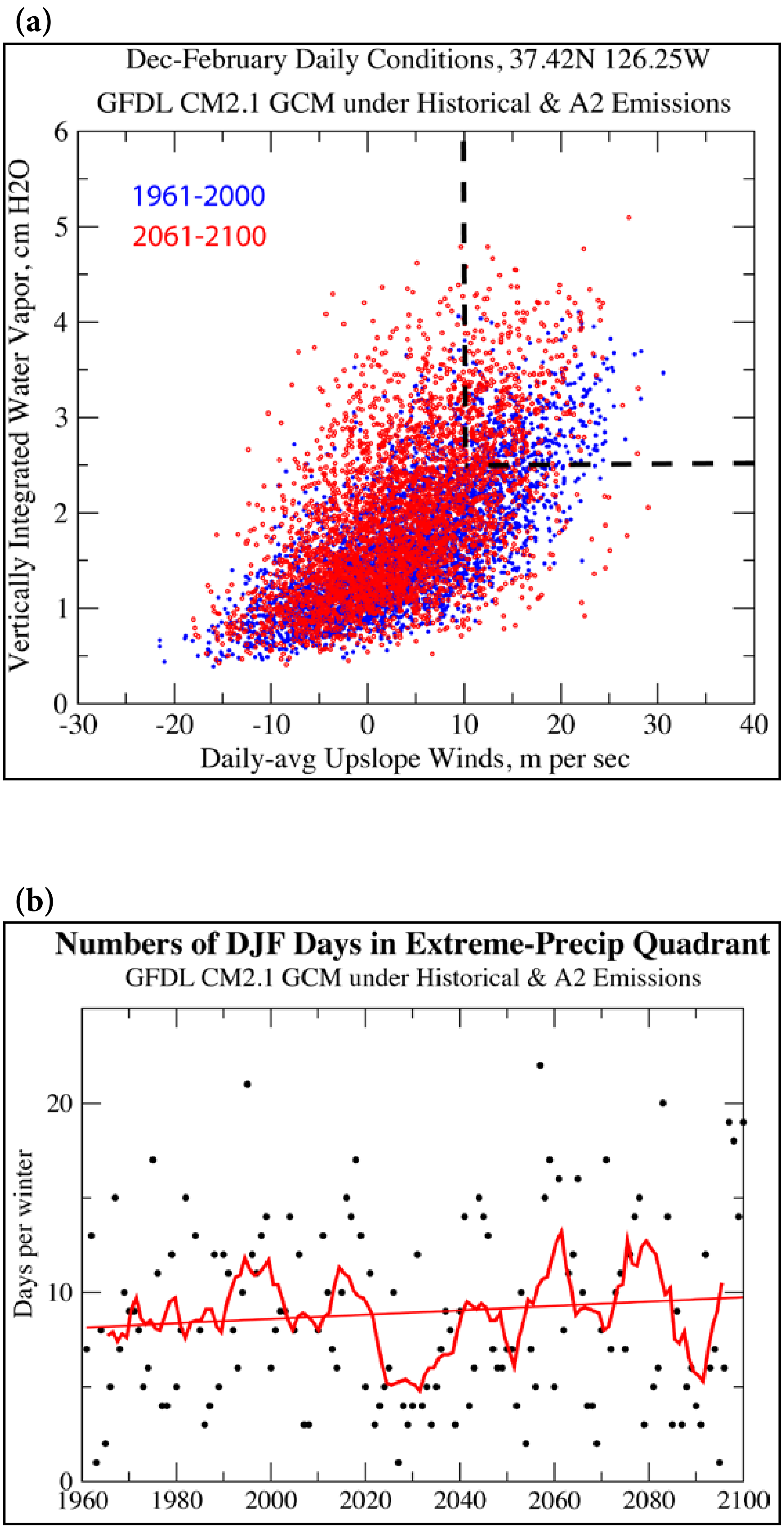


Figure 2. Plot of daily December-February integrated water vapor (IWV) and upslope wind values from GFDL CM2.1 climate model (a) and numbers of days per winter falling into the upper right quadrant of that plot (b), under evolving 20th and 21st century climate changes with A2 greenhouse-gas emissions. Thin red line in panel (b) is a linear fit to data; thicker red curve is a 7-yr moving average of data.

floods on the Russian River near Guerneville, CA, during the past 10 years have been associated with the arrival of an AR. Dettinger (2004) showed that, during the past > 50 years, flows in the Merced River near Yosemite Valley have typically risen by about an order of magnitude more following the pineapple express form of ARs than following other winter storms. From these and other examples, AR storms are now increasingly understood to be the source of most of the largest floods in California, and an evaluation of the future of floods must attempt to understand their future.

The long thin band of high water vapor amounts (yellow and orange) between roughly Hawaii and central California in the top-left panel of Figure 1, and the southwesterly band of (white) clouds in the top-right panel, is the AR associated with the New Years 1997 storm (which yielded the flood of record on many California rivers) and gives a sense of the scope and scale of these features. The other panels show other ways of visualizing the same episode. Investigations by Ralph et al. (2004, 2006), Neiman et al. (2008a, b), and others have shown that as they approach the west coast of North America, ARs are typically 2000 or more km long but only a few hundred kilometers wide (Ralph et al 2006). The air column within a typical AR will contain more than 2 cm of water vapor, with most of that vapor contained in the first 2.5 km above the sea surface and with a jet of intense and moist winds centered near about 2 km above the surface (Neiman et al 2008a). When the AR is oriented so that these intense winds carry their moist air directly up and over the mountains of California (that is, in directions nearly perpendicular and upslope into the mountain ranges), intense storms of orographically enhanced precipitation result (Neiman et al., 2002; Andrews et al., 2004).

The presence or absence of ARs along the Pacific coast can be detected by monitoring the strength of the water vapor transports across the region. The likely impact of such storms depends both on how much vapor the AR contains and how fast that vapor is being transported across coastal mountains where orographic uplift can extract the vapor as more or less intense precipitation. Intense

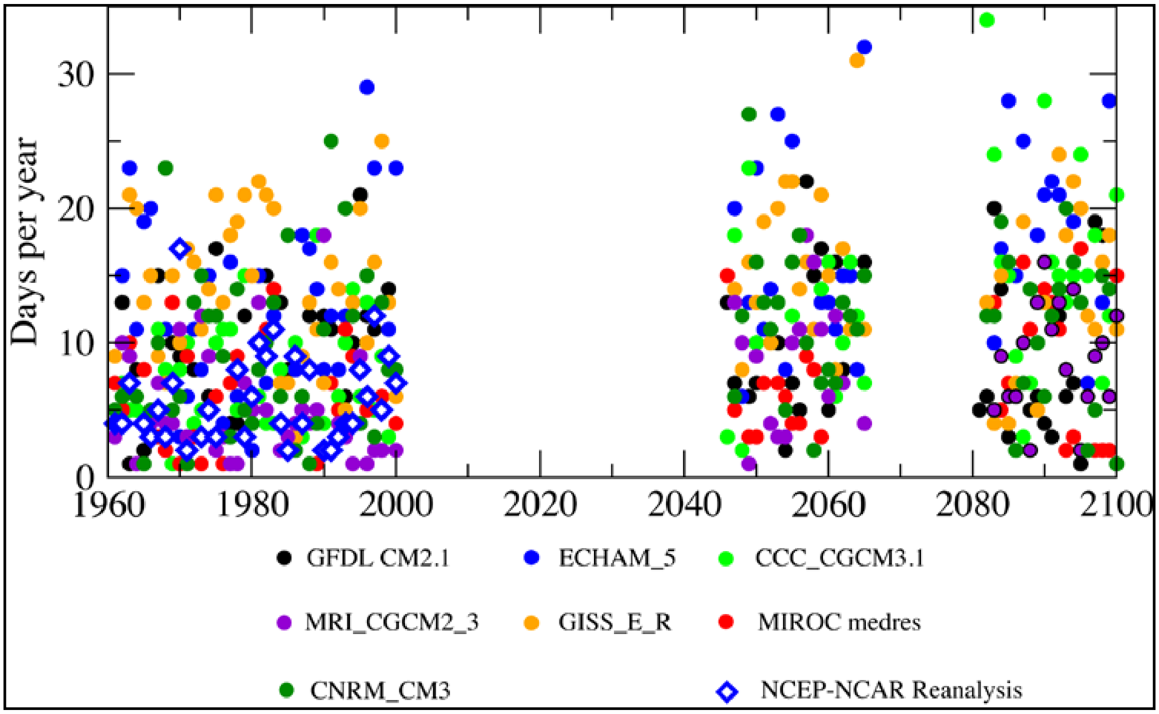


Figure 3. Numbers of December-February days per year in the upper-right quadrant of Figure 2a, for seven climate models (listed at bottom of figure) and the NCAR-NCEP Reanalysis data fields; 21st century counts are from projections made in response to A2 emissions scenarios.

"pineapple express" storms can be identified in daily general-circulation model (GCM)-scale atmospheric fields by tracing back to sources of intense water vapor transport plumes to determine which begin in the subtropics or tropics near Hawaii (Dettinger 2004). However, this can be a cumbersome algorithm to apply to current projections of climate change, because of the large fields that must be manipulated and because some of the necessary variables are not available from most of the IPCC GCMs at daily resolutions. Thus a more locally-based strategy for detecting precipitation-rich AR-type storms along the California coast, designed and now being implemented for operational forecasting (Neiman et al., 2009), is applied to climate-change projections from IPCC GCMs in the analysis presented here. The GCM-friendly AR-detection approach used here involves calculating the daily vertically integrated of water vapor (IWV) in the atmosphere and daily wind speeds and directions at the 925 mbar pressure level (about 1 km above the surface) for a GCM grid cell just offshore from the central California coast. In this study, these variables were determined for each day from the periods 1961-1980, 1981-2000, 2046-2065, and 2081-2100, and for a model-grid cell offshore from San Jose. These 20-year simulation periods are the only times for which daily water vapor, winds and temperatures were available from six of the seven IPCC models addressed here (excepting only the GFDL GCM). The wind directions are evaluated to determine the component of wind that is directly upslope on the coastal mountain ranges in that vicinity, and when the upslope wind component is greater than 10 m/s (vertical dashed line in Figure 2a) while the integrated water vapor is greater than 2.5 cm (horizontal dashed line in Figure 2a), an AR storm is declared to be occurring. In nature, all storms that dropped more than 10 mm/hour of precipitation at the NOAA Cazadero meteorological station in the past decade have met roughly these criteria. Applying the criteria above to historical and future climate simulations by seven IPCC GCMs allows us to compare the frequencies and magnitudes of AR storms arriving in California in the models under simulated historical and climate-changed conditions.

Projections of Atmospheric-River Storms

A plot of daily IWV and upslope 925-mb wind speeds as simulated by a particular climate model (GFDL CM2.1), from which complete daily data from 20th and 21st centuries was available, under historical (blue dots) and future 21st century conditions (red dots) is shown in Figure 2a. Conditions on a relatively few historical December-February days fall in the upper right quadrant of this figure, where IWV > 2.5 cm and upslope wind > 10 cm, and the number of such days increases slightly as the climate evolves under the influence of increasing greenhouse gas concentrations due to the A2 emissions scenario analyzed here (Figure 2b). The A2 emissions scenario is a scenario in which global greenhouse-gas emissions accelerate quickly throughout the 21st century. This scenario is investigated here because it provides the strongest greenhouse forcing on climate, and thus the clearest indications of directions of change amidst natural variability, among the scenarios for which climate projections were commonly available in 2009. The slight increase in number of winter days that meet the historical AR criteria (in this particular model) is a suggestion that opportunities for major AR storm with potentially attendant winter flooding might increase with warming of the climate. In this model, the upslope winds slacken notably (red dots are generally farther left on Figure 2a than blue dots), perhaps due to general weakening of mid-latitude westerly winds associated with weakening pole-to-equator temperature differences in the projections. This slackening almost compensates for the tendency of the IWVs to be larger, so that only marginally more days appear in the "extreme-precipitation" upper right quadrant. By analyzing such figures from several models and by analyzing the corresponding projected weather conditions that prevail on the days that meet the ARs criteria, key factors that will determine the intensity and risks associated with individual AR events can be inferred.

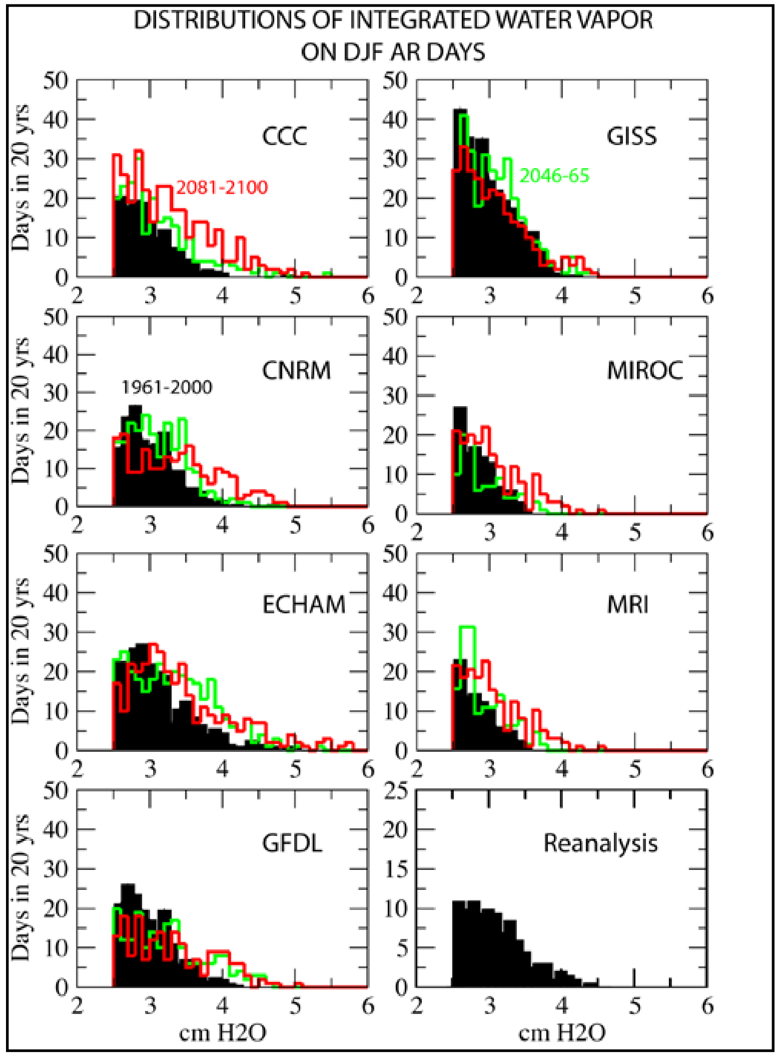


Figure 4. Histograms of simulated historical (20c3m, black) and future (A2, green and red) distributions of integrated water vapor values associated with AR-days in seven climate models and the NCAR-NCEP Reanalysis of historical observations.

The numbers of December-February days during the 1961-2000, 2046-2065, and 2081-2100 periods that have IWV > 2.5 cm and upslope winds > 10 m/s, in each of seven GCMs and in the data-assimilated NCAR-NCEP Reanalysis depiction of the historical weather record (Kalnay et al 1997, and updates thereto), are shown in Figure 3. The open (Reanalysis) diamonds represent real-world analogs to the simulated fields from the seven GCMs, and the number of Reanalysis AR episodes is on average lower than the numbers simulated by most of the GCMs (excepting the MIROC and MRI models). Nonetheless the range and general distribution of numbers of AR days per winter are not so different from the GCM counts as to preclude evaluations of the projected changes in the ensemble of GCM projections. Numbers of AR days during the 21st Century increase in most of the GCMs (compared to their respective historical counts). Most models simulate more winters in the 21st Century with exceptionally large numbers of AR storms, and fewer winters with exceptionally few opportunities, so that changes in the frequency of these "extreme" winters are more notable than the changes in long-term mean numbers of AR storms.

To be more specific, Table 1 shows how the numbers of AR days per winter change through time on a model by model basis, as indicated by linear regressions of the AR-day counts from all available winters (1961-2000, 2046-2065, 2081-2100) versus year. AR-day counts increase in five of the seven models and counts in the remaining models remains at historical levels. The projected increases in numbers of AR days in the 21st century average about +2.5 days (across the ensemble of models), or by about 30% by end of century. Thus opportunities for winter-flood generating storms in central California are generally (but not unanimously) projected to increase in frequency in projections of climate change. No basic patterns or model differences exist between the GCMs that yield more ARs and those that do not, so that the current multi-model ensemble might best be interpreted as a random sampling of possible outcomes.

The intensity and characteristics of these simulated (and observed) AR events may also be evaluated, in order to determine how AR episodes themselves may evolve in the 21st Century. Figures 4 and 5 compare distributions of IWV values and upslope wind speeds on AR days under the historical and projected-future climates from each of the seven models and in the historical Reanalysis fields. Integrated water vapor on AR days increases in all of the models, as do the numbers of AR days with IWV values greater than about 3.5 to 4 cm. In the real world, AR days with such high IWV values have been associated with the very largest storms (Neiman et al, 2008b), and thus the increases at the rightmost edges of the histograms of Figure 4 suggest rather ominous increases in the amount of precipitation that at least some of the projected AR days may deliver in the future.

Climate model	Change in # AR days / 100 yr	R**2 of trend fit (in %)
CCC	**+7.2 days**	**30**
CNRM	+2.4	4 *
ECHAM	**+4.5**	**10**
GFDL	+0.4	0.2
GISS	+0.3	0
MIROC	**+2.2**	**7**
MRI	**+3.6**	**15**

Table 1. Trends in numbers of AR days / 100 yrs from seven climate models, with trends that rise to statistical significance at 95% level highlighted in boldface, and with (*) the trend in CNRM only just missing 95% significance level.

On the other hand, the histograms of upslope wind speeds in Fig 4 indicate that, in all of the models except perhaps CCC, the upslope components of the winds transporting the additional water vapor tend to weaken as the 21st century proceeds. These weaker upslope winds will tend to work against the increased water vapor to reduce the orographic precipitation totals that the ARs might deliver. Indeed, the product of the upslope wind times the IWV gives an approximate sense of the water vapor delivered and available to be rained out of the AR storms as they pass over California's mountains. Fig 6 shows the distributions of this "intensity" product for each of the models, with the strong suggestion that in most models, although the numbers of AR days increase, the distributions of their overall (product) intensities may not change as much. Table 2 shows the regressed trends for these intensities on a model-by-model basis, indicating that three of the seven models produce statistically significant increasing trends in the winter-average intensities of AR circulations, and two more models yield increases that are not statistically significant, with season-average intensities in the remaining two models remain more or less the same. Even in the models that produce significant trends in AR intensity, the changes are not (on average) more than about 10%, which might be interpreted to translate into an average of not much more than about +10% more rain from future AR storms. Nonetheless, notice that more-than-historical numbers of ARs fall into the most intense tails of the projected distributions (Fig 6) from all seven GCMs. This tendency towards the occasional future occurrence of ARs that are more intense than any that have been witnessed historically is an indication that, as climate change proceeds, occasional AR storms are likely to be exceptionally intense.

AR storms are associated with floods because of their relatively warm temperatures as well as the intense precipitation they can deliver. The warm temperatures associated with the ARs commonly result in elevated snowlines and thus much larger than normal river-basin areas receiving rain rather than snow. The long-term AR-day and all-day averages of surface-air temperatures from the entire ensemble of projections are shown in Figure 7 for the 1961-2000, 2046-2065, and 2081-2100 epochs. In the historical simulations, AR-day temperatures average 1.8C warmer than the average of all December-February days, in close agreement with the observed (Reanalysis-based) average difference of 1.7°C. In the 21st century simulations, both AR-day average temperatures and all-day average temperatures increase, by about +1°C in 2046-2065, and by about +2°C in 2081-2100. Notice that the AR-day average temperatures warm somewhat less quickly than all days, with all days warming by about 0.1°C more in 2046-2065 and by about 0.3°C more by 2081-2100. This modest difference in the rates of average warming presumably reflects the fact that ARs involve transport of warm air from regions closer to the tropics, where overall rates of warming are less than in the midlatitudes (IPCC, 2007). Roughly, the +1.8C warmer AR storms by the end of the 21st Century might be expected to lift snowlines by about 1.8C * (1 km per +6.5C warming) or +330 m on average, thereby increasing the average basin areas that receive rain rather than snow in many mountain settings.

Finally, the seasonality of AR days was investigated by counting the numbers of such occasions for each month of the year in the historical, 2046-2065 and 2081-2100 periods (not shown here; see Dettinger et al., 2009). Generally speaking (with primary exception being the GFDL simulation), most of the increases in numbers of AR days under climate change occurred in the winter months, from about December to February. In five of the seven models, however, AR days also are projected to become notably more common in spring (CCC, GISS, MIROC, ECHAM and MRI) and autumn (CCC, GISS, and MRI). Thus, there is a widely simulated

Climate model	Change / 100 yr	% change / 100 yr	R**2 (in %)
CCC	**+5.7 cm H2O m/s**	**+11%**	**12**
CNRM	**+4.0**	**+ 9%**	**8**
ECHAM	**+3.8**	**+ 7%**	**6**
GFDL	+0.1	0	0
GISS	+1.6	+ 4	3
MIROC	-0.3	- 1	0
MRI	+2.1	+ 5	3 *

*Table 2. Trends in intensity (IWV * upslope wind speed) of AR days / 100 yrs from seven climate models, with highlighting as in Table 1.*

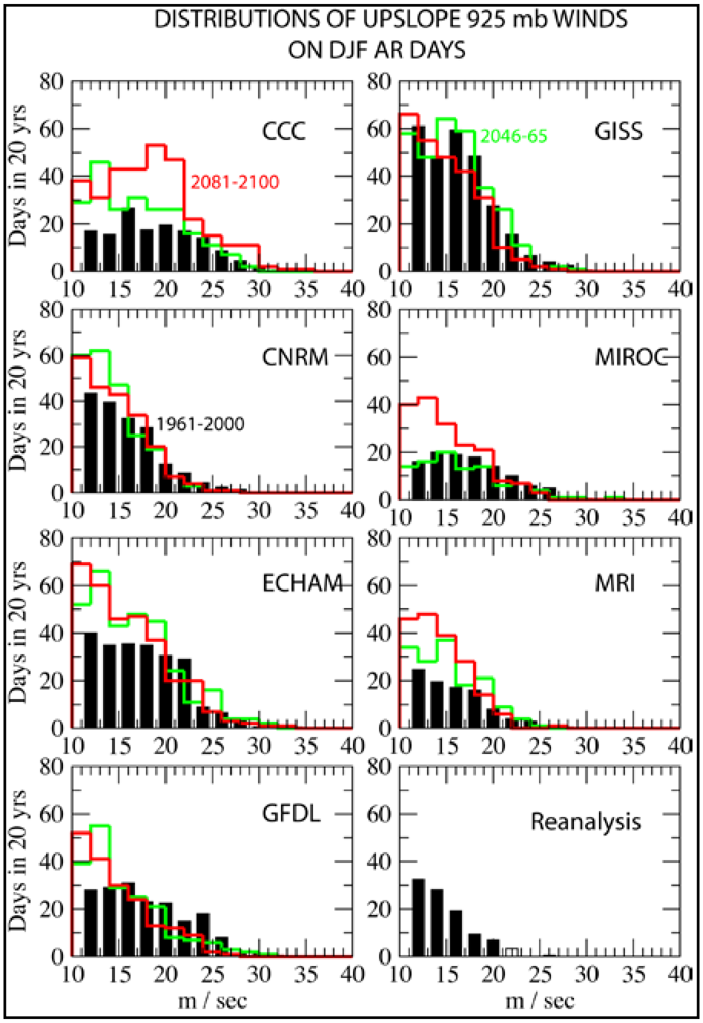


Figure 5. Same as Figure 4, except for upslope winds on AR days.

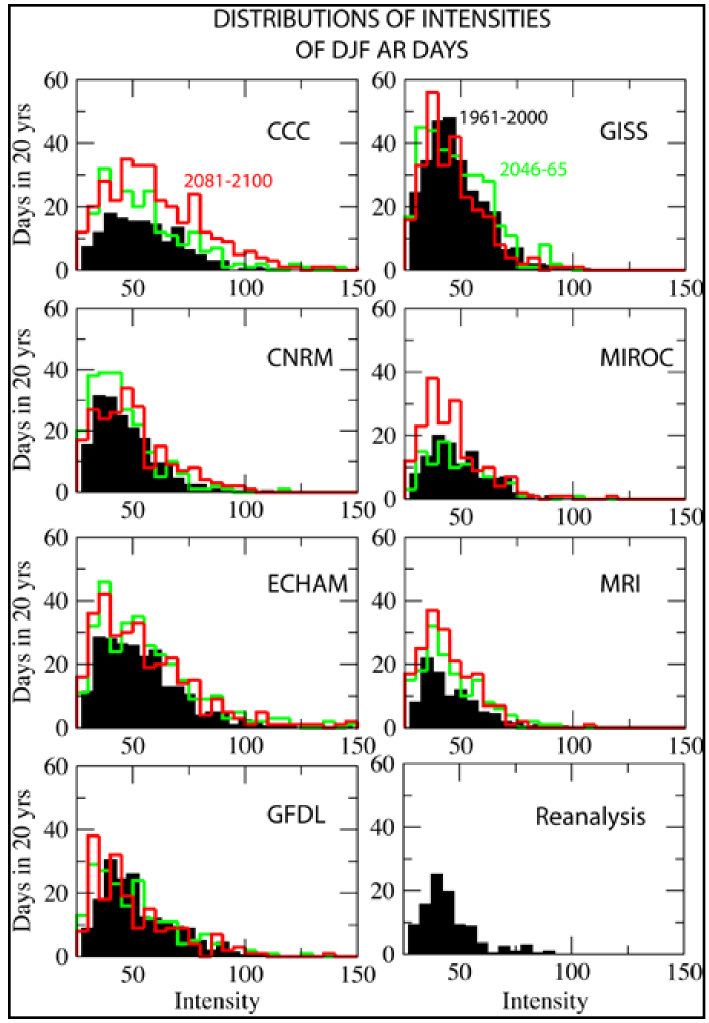


Figure 6. Same as Figure 4, except for intesities (IWV * upslope wind) on AR days.

potential for expansion of the season when AR storms might occur. This may imply more potential for increased flooding before and after the historical bounds of flood season in California.

Conclusions

Major storms, in particular "pineapple express" or atmospheric river storms, were assessed here in the context of projected climate changes. Projected changes in these storms are mostly at the extremes: Years with many AR storms become more frequent in most climate change projections analyzed here, but the average number of such storm per year are not projected to change much. Likewise, although the average intensity of these storms is not projected to increase much in most models, occasional much-larger-than-historical-range storm intensities are projected to occur under the warming scenarios. Finally the AR storms warm along with, but not quite as fast as, the general mean temperatures in the seven projections analyzed.

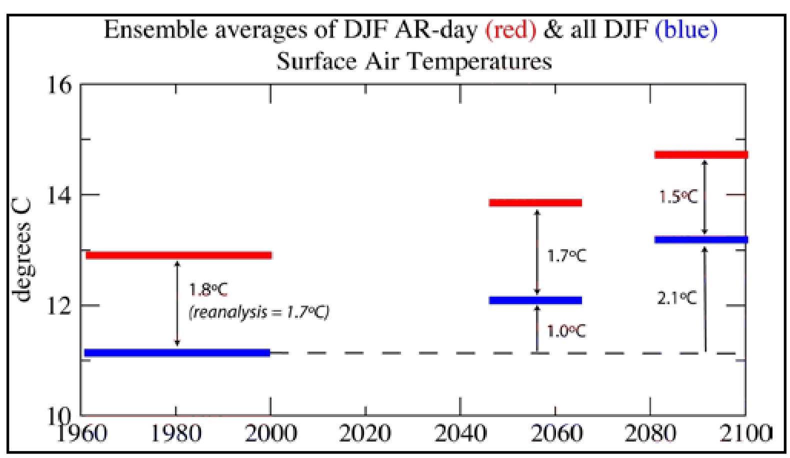


Figure 7. Ensemble average temperatures on December-February AR days (light) and on all Dec-Feb days (dark) under conditions corresponding to Figures 4-6.

Together these findings suggest that California flood risks from the warm-wet, atmospheric-river storms may increase beyond those that we have known historically, mostly in the form of occasional more-extreme-than-historical storm seasons. More analysis is needed to increase understanding and certainties about this potential, but the analyses might serve as an example of how attention to details of how specific causes of flooding are projected to change (in this case, the frequency and magnitudes of AR storms) may provide early insights into how the overall risks of flooding may eventually change.

Acknowledgments

Research described here was supported by both the California Energy Commission-funded California Climate Change Center and the CALFED Bay-Delta Program-funded Computational Assessments of Scenarios of Change in the Delta Ecosystem (CASCaDE) Project. These results were presented and discussed more fully in a report to the California Climate Action Team's 2008 biennial climate-change impacts assessment (Dettinger et al., 2009).

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Biography

Michael Dettinger is a research hydrologist for the U.S. Geological Survey, Branch of Western Regional Research, and a research associate of the Climate, Atmospheric Sciences and Physical Oceanography Division at Scripps Institution of Oceanography, La Jolla, California. Dettinger has monitored and researched water resources of the West for over 25 years, focusing on regional surface water and groundwater resources, watershed modeling, causes of hydroclimatic variability, and climatic-change influences on western water resources. He has authored over 75 scientific articles in scholarly journals and books, 20 government reports, and another 70 articles in outreach and less formal outlets. Among other activities, he was the physical-sciences team leader for DOI-DOD ecosystem planning in the Mojave Desert, founding member of the multi-institutional CIRMONT Western Mountain Climate Sciences Consortium, climate advisor to the CALFED Science Program, member of the Climate Change Technical Advisory Group for DWR's 2009 Water Plan Update, and member of the external Science Steering Group for the multi-agency federal Global Water Cycle Program. He has degrees from the University of California San Diego, Massachusetts Institute of Technology, and a Ph.D. from the University of California, Los Angeles (Atmospheric Sciences).

Flood Frequency Based on Climate Projections

David Raff, U.S. Bureau of Reclamation

My intro is that I am going to portray a different view, and that is, why should we be considering projections? Let's speak about it from a financial standpoint. Here's a Barclay managed funds report identifying that for three previous years they are showing three-year annual returns anywhere from a hundred percent to 37 percent, and this was in 2007. If you read the fine print, which we of course now know was the actual important thing between 2007 and now, is that past performance is not indicative of future results. To say it another way, what's wrong with this picture, beside the fact it's a lion, is that he is facing backwards. We don't try to go forward, necessarily, always looking behind us. And if I can drive on that point, what is the actual danger of riding our bike facing backwards, then that would be the point of my talk.

So what are the key points? In fact, our presumed risk assessments, based on an expanding retrospective view, result in biased estimates of our risk. And that is in the case of a monotonically moving distribution. Second point is that a monotonically moving distribution, as we've heard, is not even an unreasonable expectation, which is, in fact, why we're looking for it. Third, it may not be reasonable to expect, as Mike Dettinger said in his talk, that we will necessarily be observing changes in floods as fast as they are moving. Every gauge, every experiment, is a one-off thing. So it's not necessarily reasonable to expect that we can see these trends as quickly as they're happening. Four, it is feasible to consider climate projection information to determine how our presumed risk may be mischaracterized.

So these are very conceptual type of statements. I am not saying that we should be moving towards doing risk analysis simply based off climate projections, but that we need to be considering what is in store in the future as we are identifying what our risks are today. What does this mean? Obviously, and this is just an example. Beth Faber said something similar yesterday about stationarity and confidence. I am not going to get into definitions of stationarity and non-stationarity. I would prefer it if we had just left that off at this point and say, how do we do flood frequency better?

This is the expanding retrospective view. There is some time series, and there is some confidence about our estimates which is a function of the estimate of our standard deviation over the time period that we're observing it. From that we can develop some flood frequency curve that is shown theoretically in green with some estimates of confidence about that green curve that is shown by the shaded gray.

At some point in the future, we have an additional set of observations, and it is our belief that if we are using Bulletin 17B, that we are now held constant our estimate of our standard deviation, but we have increased N, and therefore, we can make a new prediction of flood frequency which is now the red curve, and we have reduced our confidence limits about that curve, meaning, then, that we're honing in on an answer. And again, with the expanding retrospective view, we continue to add years, and we continue to do better making our estimates.

What is the problem with this? As has been shown yesterday and in a number of different ways, if in fact S is changing, but if it is changing slower than the number of years that we are adding, then, in fact, we are not only biasing our estimate in the flood frequency curve, but we are significantly overestimating our confidence. Our confidence intervals are getting smaller, even though we are drifting away from the actual risk.

The experiment that I would like to share with you today was conducted on four basins that were meant to be geographically distributed throughout the western United States, one being the James River in the upper Midwest; the Boise River, which is in central Idaho; the San Joaquin, which is in central California; and then the Gunnison River, which is in the high mountains of Colorado. As opposed to trying to show all four sets of information, because your interests may lie in the methodology here, I am going to focus on one of these basins, the San Joaquin, but I will show some quick results from the other basins later.

What is the methodological element? How do we explore the use of climate projections to develop flood frequency? First, we need to establish where we are going to look and, in this case, establish three different look-ahead periods throughout the 21st Century: 2011 to 2040, 2041 to 2070, and 2071 to 2099. Then we obviously need to have some sort of projections, and I will go through one rationale for selecting which projection to use. Then we will use those projections to drive a hydrologic tool to go from temperature and precipitation projections to actual stream flows. I will spend a little bit of time discussing how that methodology performs for the retrospective period. Then we will start to explore what this means for an expanding retrospective view of flood frequency. I won't actually get into the drivers of change, just for time's sake.

Here are some general "is and isn't's." This does not utilize General Circulation Model (GCM)-based information on extreme precipitation. We have heard that these are a major flaw of the GCMs, and therefore, we are not going to use them. It does, therefore, assume there is some correlation between monthly GCM characterization and historical observed rainfall events. So there is, in fact, a remaining assumption of stationarity here that we can use some analysis of the retrospective period to characterize - to be used when we use the projections. This does not attempt to assign probabilities to the climate projections. What it is doing is to explore what the projection variability says about potential floods in the future.

It does presume that Bulletin 17B procedures are a reasonable comparison basis between an expanding retrospective view and an alternative view. It also assumes that the hydrologic processes as represented within the hydrologic model, going from temperature and precipitation to stream flow, is something that is consistent in the past and will be in the future. So those are some of the major "is and isn't's."

What are the projections and how do we choose them? Levi Brekke discussed this. Levi, along with his colleagues Ed Mauer in particular and Tom Pruitt, developed a down-scaled archive, which I know many people in this room are very aware of. They have approximately 116 projections of 21st Century climate, including the retrospective period of 1950 to 2000, downscaled the climate projections for various models - I believe it's 16 or so models, and various runs and various emission scenarios, and these are archived for total of about 112 - I can't remember the exact number - 112 or 116 total projections.

What do those projections happen to say in general about this area of California? It is obviously a warming trend up to about 6 or 7 degrees, but a general reduction in rainfall. As I mentioned above, we are not going to run all the projections, and we are not going to assign probabilities to the projections, but we are going to select from those. And how are we going to select from those? In this little graphic - ignore the blue squares for a minute and just focus on the fact that there are a lot of numbers there. There are actually 116 numbers, and those 116 numbers represent each of the projections for this period, which is this 2011 to 2040 period relative to a base period defined as 1971 to 2000. What you can see here is that all the projections show an increase in temperature for that period on the Y axis, between a ratio of 1.02 to about 12 percent, and on the X axis is a ratio of precipitation showing some with modest decreases, the majority of the cluster showing about no change in precipitation, and then there are a number on the far right side of the X axis showing some increase in projections.

Now, the actual selection of which models to actually consider. The goal is to consider the envelope of variability. It is to then select this tic-tac-toe pattern, which are now the blue squares. So you select the models that are closest to these tri-quartile distinctions in both temperature and precipitation for a total of nine selected projections encompassing the majority of the variability shown by the entire suite. This is done for each of the three look-ahead periods. Something to note is that, in fact, rarely are the same models considered or the same projections considered for each of the future periods. This is for a variety of reasons. As Levi noted, there is obviously interdecadal variability, low-frequency variability going on, as well as models drift relatively close to each other.

If you were to look at the wettest and the hottest projection in that first time period, that wettest and hottest projection has now become about in the middle of the distribution for the last period. The meaning of this is that if you are trying to continue to have this envelope of variability, you actually have to change which models you are looking at.

Now I have a selected set of temperature and precipitation projections, which I want to run through a hydrologic tool. The hydrologic tool in this case is the Sacramento Soil Moisture Accounting Model (SAC-SMA) model. This one used here was developed for the San Joaquin River. It is the operational model for the National Weather Service River Forecast Center in this area, meaning that it came to us pre-calibrated, at least over the antecedent period, so we accepted that calibration. If it is good enough for them, it is good enough for us. We then can proceed to drive this SAC-SMA model with our climate projections.

The climate projections, as have been discussed, are in monthly blocks of temperature and precipitation. Obviously, floods are not driven by monthly statistics. So we need to go from monthly to something reasonable; in this case, a SAC-SMA models driven by six hourly temperature and precipitation. How is this done? We have a calibration data set that comes from the National Weather Service, which are the six hourly values of temperature and precipitation for their entire calibration period; in this case, 1947 to 1997. For each month of the projections for both temperature and precipitation, you select a month that is close as the retrospective period, and you scale up the six hourly values of those smaller increments such that they match the monthly projected values. It is a delta method to match the projected temperature and precipitation, using the actual observed historic temperature and precipitation. That is the remaining assumption of stationarity in this project.

Does that methodology at least work for the retrospective period? What exactly do we have to evaluate that with? For the retrospective period, we have 1947 to 1997. We have selected nine projections per look-ahead, which is a total of 27 projections. We have three look-aheads. We then, because there is some randomness component to how you do the temporal downscaling, going from monthly to six hourly values, because it's representing a near month. It doesn't have to be in the same month every time. We did this 10 times per. So nine projections to look ahead, three look-ahead periods, ten simulations per projection. We have 270, and then we have 50 years of simulation for each of these over the retrospective period. That results in a series of about 13,000, not about, exactly 13,500 samples of retrospective annual maxima, driven by the climate models' projected retrospective period. It also results in 10 times 30 times 9, or 2,700 samples, for each look-ahead period.

On the figure, the calibration set is in blue. The gray represents each of these 270 simulations over the retrospective period. That is an empirical cumulative distribution function on the Y axis and a flow rate expressed as meters cubed per second on the X-axis. I know our international guests will be happy about that; for the Americans, I can't translate for you at the moment. The point here is that the gray cloud encompasses the blue, although there is obviously some variability around it, but my argument for this is that, at least visually, over the majority of the frequency distribution, it does a reasonable job of encompassing the actual calibration set of floods.

What does it look like in the future? In terms of the future period, the blue represents the retrospective period, which is held constant. Obviously, that is essentially the accumulation of all 270 of those retrospective runs. Green is the accumulation of the 2,700 annual maxima simulated from the 2011 to 2040 period; the yellow is the accumulated 2,700 annual maxima simulated for the 2041 to 2070 period; and likewise, red for 2071 to 2099. It is obvious to see here again an empirical distribution function for the Y axis and flow rate on the X axis, and you do see this monotonically moving shift in flood magnitudes. Here is where I will make my point that if this is the reasonable expectation of the possible futures, because these are a number of futures that have been simulated by a number of different climate projections. The floods that occur relatively frequently are not changing very much, but there is an increase in the higher magnitude, less frequent floods. It is not reasonable to say that we expect to see a linear trend.

You may ask, is this just some function of the methodology? I would say that at least some physical processes are being represented, because the other three basins show very different results. The Boise shows a much different pattern. Floods for almost all exceedance probabilities are larger in the three look-ahead periods. The Gunnison actually shows relatively little change, and in fact, it says that the more common floods should be getting smaller, but the bigger floods may - there is some break point there. So, again, detection is not to be expected in this case. Then likewise, the James River, which is something that was talked about yesterday by Pat Foley. The James actually showed that for a lot of the flood distribution, there is relatively no change, but again, a shift in only one portion of the exceedance probability distribution. So, again, detection. You cannot necessarily expect to see changes unless we change the way we are looking for them. It is a problem that each gauge is a one-off experiment in this case.

Now, what does this mean in a practical sense for how we do flood frequency? We have 2,700 annual maxima for each look-ahead period, and we have 13,500 annual maxima for the retrospective period from 1950 to 2000. The current paradigm is this expanding retrospective view where every year we have new data that we bring in and we add it to our time series, and then for this particular argument, we are fitting a Bulletin 17B type procedure to that expanding retrospective view. I am contrasting that with what I am calling this moving window approach, where I am only using a recent set of floods rather than the entire period of record.

For the expanding retrospective viewpoint, at each time period, looking at three time periods in the future, I randomly select 30 from the 13,500 antecedent periods. Then for the nearest term, I add 30 years, randomly selected from the 2,700 floods generated in that time period. So for this first period, I then have a sample size of 60 that I'm going to fit a Log-Pearson III curve. For the 2041 to 2070 period, the same procedure, except that now you're adding 30 randomly selected from that 2,700, for a total of 90 for the total length of record for the middle period; and again, you have another 120 years of record in this out point. So that's the expanding retrospective method experiment. Then for each of those time periods, I fit a Log-Pearson III type distribution, similar to Bulletin 17B, and I do this a thousand times or so, and so then I have a thousand flood frequency curves for each of these look-ahead periods.

For the moving window, so for the first period, I am only selecting 30 years from that portion. For the middle period, I'm only selecting 30 years, meaning that I'm saying that the climate at this point is the only thing I'm going to consider. Again, I am only selecting 30 years from the 2071 to 2099 period. What does this mean for how we characterize flood frequency? On this plot are those fitted Log-Pearson III distributions, the solid line in blue represents the median of that little Monte Carlo experiment of the thousand generated floods. The dotted blue lines represent the 25th quartile and the 75th quartile of the Monte Carlo experiments. They are not confidence intervals about the solid blue curve. They are a quartile of the actual distribution of flood frequency curves.

The green in contrast is the moving window perspective. Again, the moving window perspective with the dotted lines, also representing selections from the Monte Carlo experiment, not confidence intervals about it. The point here is that you may still think you're doing okay. In this expanding retrospective view, the actual median is not much higher than the 75th quartile of your expanding retrospective analysis. But at some point in the future - and this is important if you are designing something or you are fixing for a risk for a much longer look-ahead - is that your expanding retrospective view is actually beginning to collapse on itself. Because you have 120 years, the standard deviation over the square root of N. N is larger.

The 25th and 75th quartiles of the flood frequency distributions become nearer to each other and are nowhere near what floods are actually being simulated for in that 2071 to 2099 period. It is similar to saying, why am I seeing a 200-year flood five times in the past 10 years? Because you are sampling from a totally different distribution than what you are characterizing your return periods from.

Thank you.

And just to reiterate, shameless plug number 1. Something I've heard in a number of conferences, workshops, from researchers in the past is—what are the water management needs with respect to climate change? There is USGS Circular 1331 that is out there if you are a researcher, and discusses what our needs are. It's there, and then this work that I have presented today was something that came out a couple months ago. Thank you.

***NOTE:** This is a transcript of the author's remarks at the workshop that has not been reviewed or edited by the author.*

Biography

David Raff is the technical specialist for the Flood Hydrology and Emergency Management Group at the Bureau of Reclamation. David work focuses on understanding and prediction of extreme hydrologic events focused on the evaluation of hydrologic risk and uncertainty. He is also focused on climate change and water resources management and seasonal to inter-annual water forecasting. David's education includes a B.S. in Electrical Engineering from Tufts University and a M.S. in Rangeland Ecosystem Science and a Ph.D. in Civil Engineering from Colorado State University.

RECLAMATION

Managing Water in the West

Flood Frequency Based on Climate Projections

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Technical Service Center
Flood Hydrology and Emergency Management Group

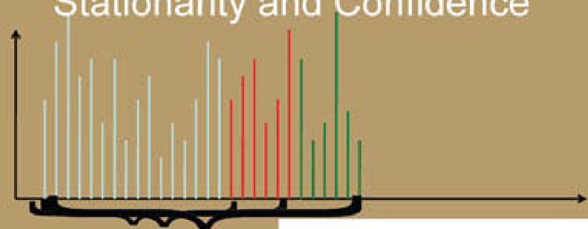
U.S. Department of the Interior
Bureau of Reclamation

Key Points

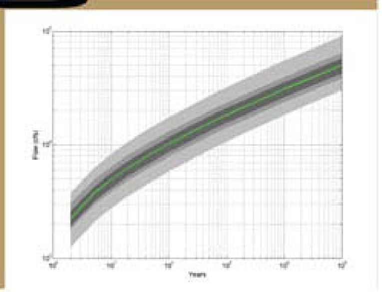
- Presumed Risk based on "Expanding Retrospective" results in biased estimate of floods for a monotonically moving distribution.
- A monotonically moving distribution is not an unreasonable expectation.
- It may not be reasonable to expect that we will be observing the changes in flood as fast as they are changing.
- It is feasible to consider climate projection information to determine how our presumed risk may be mis-characterized.

RECLAMATION

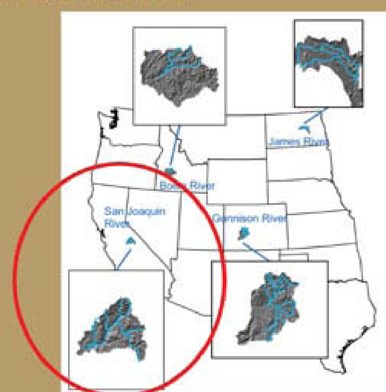
Stationarity and Confidence



$$CI = f\left(\frac{S}{\sqrt{n}}\right)$$



Basin Selection



RECLAMATION

Methodological Outline

- Establish Look Ahead Periods
  - 2011 – 2040, 2041 – 2070, 2071 – 2099
- Choose Projections from possible projections
- Run Projections through NWS operational Model
- Evaluate capability of rainfall-runoff model for evaluation
- Do Flood Frequency Analysis of Expanding Retrospective vs. Moving Window by lookahead period
- Drivers of Change

RECLAMATION

General IS and ISNTS

- DOES NOT utilize GCM based information on extreme precipitation – DOES assume monthly GCM characterization to observed rainfall relationships stationary
- DOES NOT attempt to assign probabilities to climate projections. DOES attempt to describe variability in projections.
- Presumes Bulletin 17B procedures are a reasonable comparison basis
- Assumes that hydrological processes consistent in the past as in the future.

RECLAMATION

Methodological Outline

- Establish Look Ahead Periods
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RECLAMATION

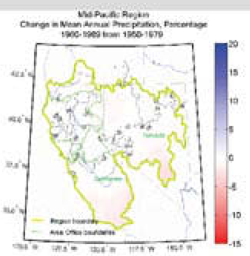
Projection Selection – Downscaled GCM Archive

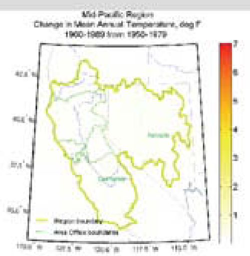
Mauer et al. 2008
http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/

- Projections Menu
  - Range of climate models and emission scenarios
- Membership Criteria
  - Focus on climate models that had simulated SRES A1b, A2, B1, and had participated in the "20th Century Climate Experiment"

#	WCRP CMIP3 Model I.D.	# A1b	# A2	# B1
1	BCCR-BCM2.0	1	1	1
2	CGCM3.1 (T47)	1…5	1…5	1…5
3	CNRM-CM3	1	1	1
4	CSIRO-MK3.0	1	1	1
5	GFDL-CM2.0	1	1	1
6	GFDL-CM2.1	1	1	1
7	GISS-ER	1	2, 4	1
8	INM-CM3.0	1	1	1
9	IPSL-CM4	1	1	1
10	MIROC3.2(medres)	1…3	1…3	1…3
11	ECHO-G	1…3	1…3	1…3
12	ECHAM5/MPI-OM	1…3	1…3	1…3
13	MRI-CGCM2.3.2	1…5	1…5	1…5
14	CCSM3	1…4	1…3, 5…7	1…7
15	PCM	1…4	1…4	2…3
16	UKMO-HadCM3	1	1	1

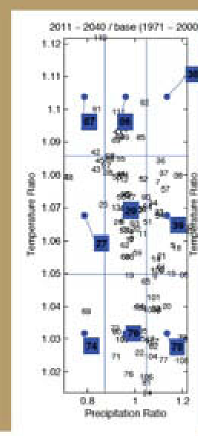
Climate Projections





RECLAMATION

Projection Selection

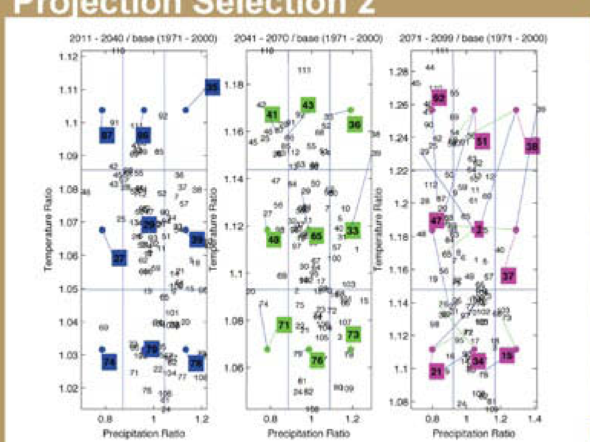


•Projections Selected to encompass the variability portrayed by the suite of model projections in archive (tic-tac-toe pattern).

•Projections for each look ahead vary as projections "drift" in T and P through time relative to each other.

RECLAMATION

Projection Selection 2



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Methodological Outline

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RECLAMATION

Rainfall Runoff Modeling

- Projection T and P used to select from calibration set an historic month.
  - Select closest (T,P) from any historic month and scale by T and P (8 sq) ~ 12 * 50 / 4 = 150 possibilities

RECLAMATION

Methodological Outline

- Establish Look Ahead Periods
  - 2011 – 2040, 2041 – 2070, 2071 – 2099
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- Run Projections through NWS operational Model
- Evaluate temporal disaggregation and rainfall-runoff model
- Do Flood Frequency Analysis of Expanding Retrospective vs. Moving Window by lookahead period
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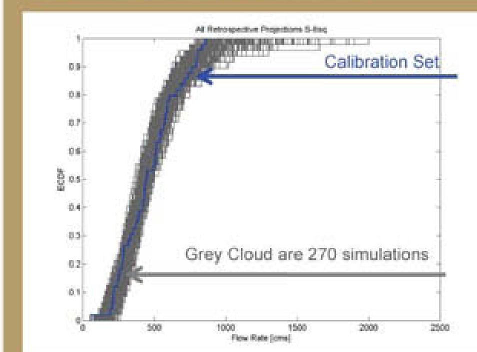
RECLAMATION

Model Runs – Retrospective (1947 – 1997)

- 9 projections per lookahead
- 3 lookaheads
- 10 simulations per projection
- 50 years per simulation
- = 13,500 sample of Retrospective Annual Maxima
- = 10 * 30 * 9 = 2700 samples for each lookahead

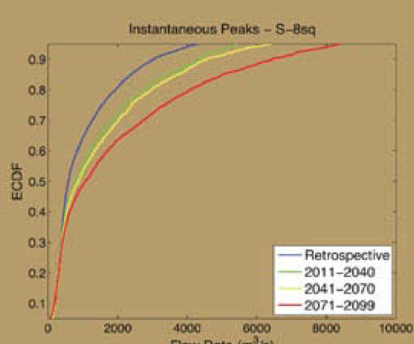
RECLAMATION

Methodological Results for Antecendent Period



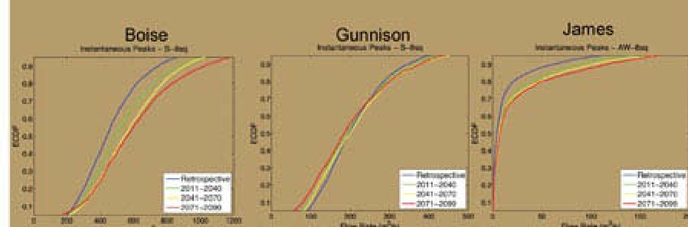
RECLAMATION

Non-Stationary Distribution Floods get bigger through time



RECLAMATION

Are all Results the Same?



RECLAMATION

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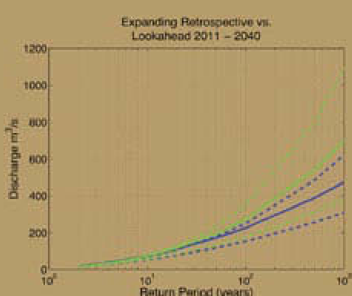
RECLAMATION

Expanding Retrospective vs. Moving Window

- Randomly select annual maxima from simulated results and fit LPIII distribution to them.
  - "Expanding Retrospective" chooses
    - 30 Retrospective
    - + 30 2011 - 2040
    - + 30 2041 – 2070
    - + 30 2071 – 2099
  - "Moving Window"
    - Only 30 from 2011 – 2040
    - Only 30 from 2041 – 2070
    - Only 30 from 2071 - 2099

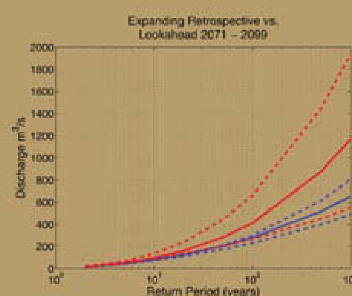
RECLAMATION

Expanding Retrospective vs. Moving Window 2011- 2040



RECLAMATION

Expanding Retrospective vs. Moving Window 2071 - 2099



RECLAMATION

Estimating Uncertainty in Future Climate Projections

Dave Stainforth, Grantham Research Center, London School of Economics

Abstract

Many decisions taken today will have long term consequences on time scales ranging from one or two decades to 50 or 100 years or beyond. Flood protection measures and water resource planning involves substantial investment in assets which we hope will be fit for purpose for such very long periods. Yet over these time periods we expect the earth's climate to undergo substantial further changes as a result of anthropogenic emissions of greenhouse gases; this comes from basic physical understanding. It is therefore sensible to make such decisions in the context of these changes. Perhaps the greatest applied science challenge today is to provide robust, relevant information which can be used to guide such decisions. Complex climate models are the principle tool used for this purpose at present. Yet such decisions are made at relatively small scales and are influenced by many variables such as temperature, precipitation, frequency of intense events, longer term "extreme" events etc., while climate modelling has greatest confidence in statements about temperature at very large scales (Randall et al., 2007). The exploration and communication of uncertainty and confidence is therefore a high priority. Here the fundamental challenges in extracting probabilities about future climate are presented through discussion of four key barriers to the generation of quantitatively decision-relevant probabilities for future climate. An alternative approach to the interpretation of ensembles of general circulation models is also discussed. These issues have significant implications for both the use of climate model information in adaptation planning and the design of future models and experiments which could provide information of value to decision makers.

Introduction

Climate change is only one of many drivers in most long terms decisions. Financing, population shifts, engineering constraints and changes in demand characteristics are examples of others. Nevertheless, to the extent that climate change is a driver in such decisions it is valuable for society to consider this driver appropriately. A common response to this situation is to view the challenge as one in which we should optimise our decisions over predictions which take the form of probability distributions; the "predict and optimise" approach. Here I argue that the science of climate physics and modelling faces significant barriers in providing probabilities which can be used in such an approach. Through appropriate study of these barriers we can hope to provide more relevant and reliable information today while improving the design of our models, and our modelling experiments, in ways which will enable us to provide better information in the future. Ignoring or overlooking these barriers, however, risks misrepresentation of what our models are telling us and has the potential to encourage mal-adaptation. It also has the possibility of undermining the credibility of climate science. This latter point has profound risks in terms of undermining the robust science which underlies the need for significant climate change mitigation measures.

Climate is of course a highly complex system involving not just complicated dynamics but also interactions of the dynamics with radiative processes, phase change processes, chemical interactions, land surface processes etc. Some aspects of the system can be studied mathematically with either analytical or numerical solutions, but the interactions of many parts of the system can only be studied using complex climate models. These models have components representing many separate but interacting aspects of the system. They are impressive research achievements in themselves and are powerful research tools. As research tools they are invaluable in helping us understand the system, providing further evidence to support theoretical understanding, and suggesting relationships and mechanisms for which further evidence can then be sought either in observations or theory. They are also the only tools which provide information on regional or even local scales;

scales which begin to appear relevant for practical adaptation decision making. It is not surprising therefore, that in recent years they have begun to be used not just for research and process understanding but also for climate prediction on these scales (Murphy et al., 2009). It is in this context that it is useful to consider the challenges in using these models to support water resource management.

Illustrating the Problem

Figure 1 illustrates the limited degree to which current models explore uncertainty in the regional response to increases in atmospheric greenhouse gases. It shows the change in winter temperature and precipitation in the "Giorgi" region (Giorgi, 2000) of Eastern North America in response to doubling atmospheric carbon dioxide levels. Each point represents a different model or model version (Stainforth et al., 2005). Each is either an eight or ten year model mean, and therefore some form of "climate mean", albeit over a relatively short period. The diamonds show the ten year mean winter response for each of fourteen different climate models from the CMIPIII archive (Meehl et al., 2007). These models have many similarities but also many differences; many come from different modelling centres around the world. An indication of the variability in the ten year mean is shown by the error bars. Although showing quite a wide range of temperature response they show relatively little variability in precipitation change. This can be contrasted with the crosses. These come from the climateprediction.net project (Stainforth et al., 2005, Stainforth et al., 2004) which involved a systematic exploration of the implications of parametric uncertainty in one model. There are many important differences between the two datasets – in particular the diamonds represent a mean ten year response in a single simulation while the crosses are eight year means across initial condition ensembles of varying size; some with only single simulations. The CMIP III models (diamonds) contain a dynamic representation of the oceans while the model used in these climatprediction.net results (crosses) has a thermodynamic ocean. The point here is only to illustrate that today's state of the art climate models (the diamonds) significantly underestimate uncertainty in the potential regional response to increased atmospheric greenhouse gases. This is true in other regions of North America and around the world too. (See Figures 2 and 3.)

The last IPCC report stated that "there is considerable confidence that climate models provide credible quantitative estimates of future climate change, particularly at continental scales and above." (Randall et al. 2007). Of course most water

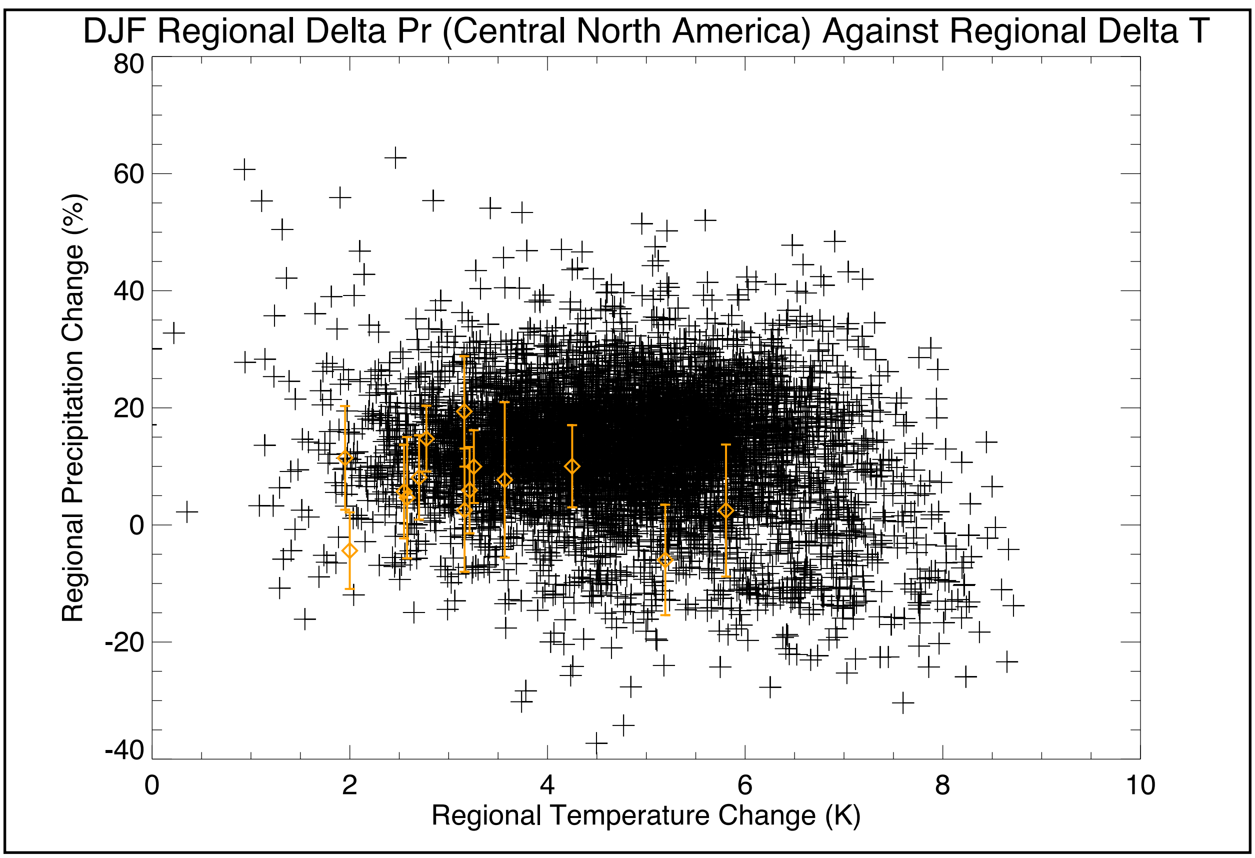


Figure 1

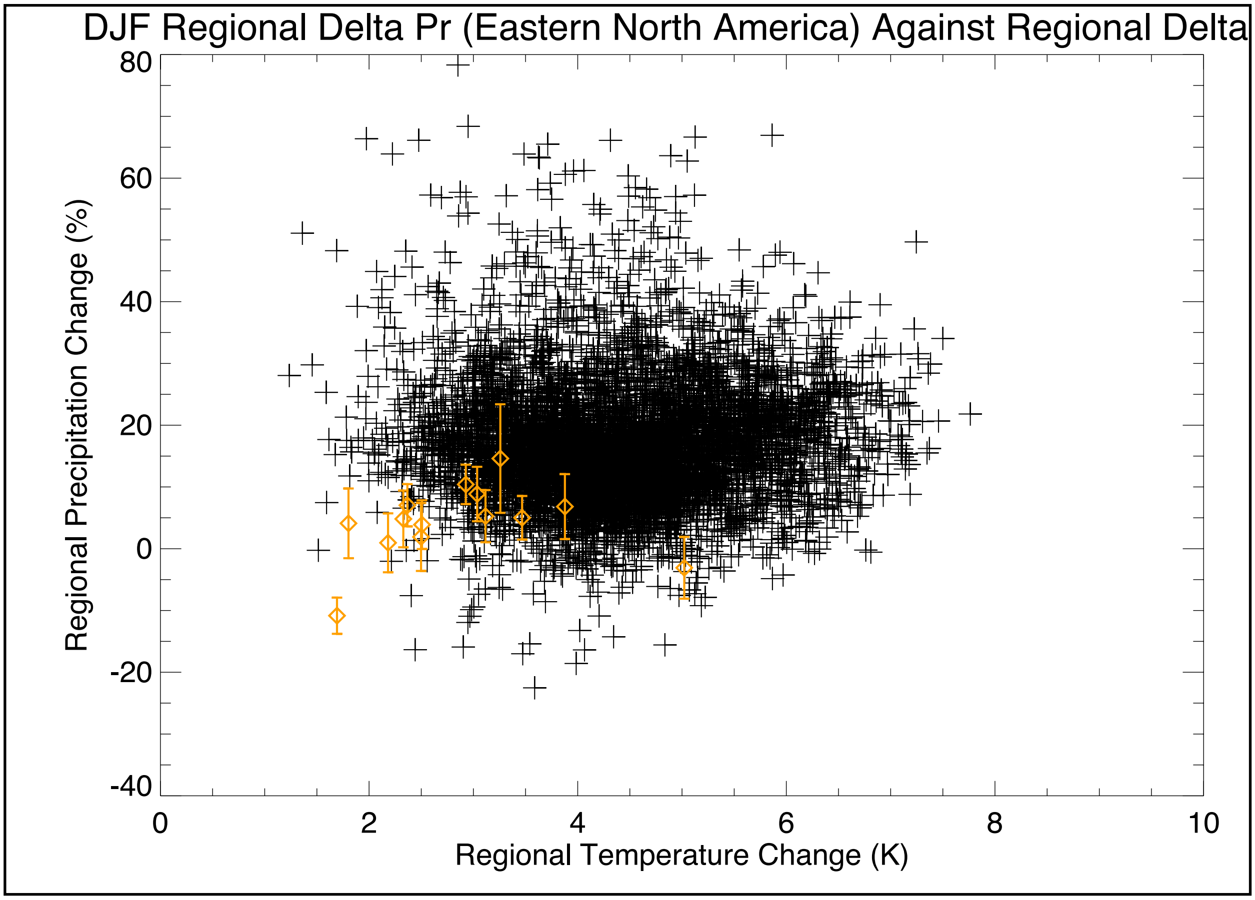


Figure 2

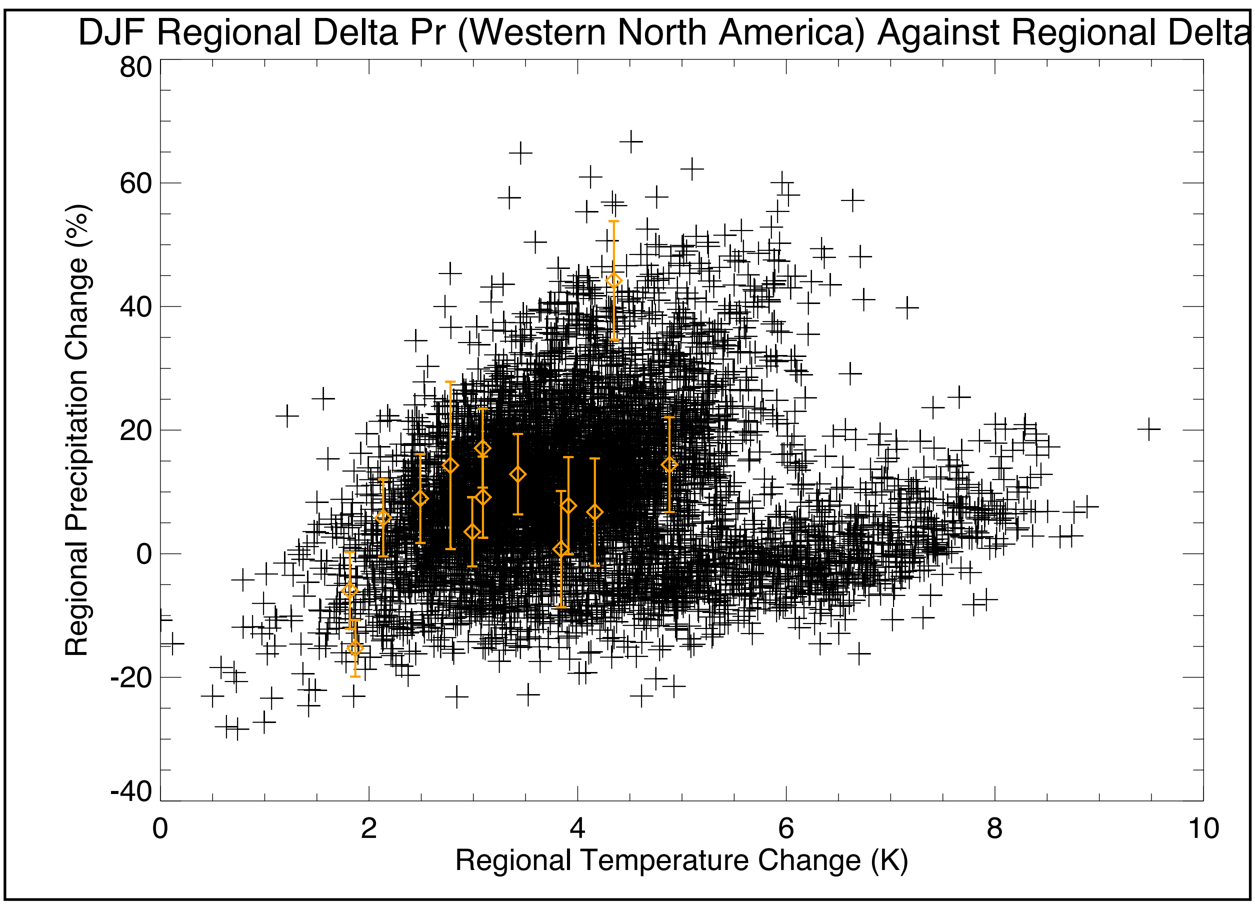


Figure 3

resource planning takes place on scales much smaller than continental. Even the regional information shown in Figures 1, 2 and 3 may be too large scale for many decision makers. As a consequence, many impact and adaptation studies use regional models. These provide more detailed regional information but they are driven by information from global models. Although the spatial resolution is higher, regional models can not reduce the uncertainty from the global models. Indeed as prediction tools they add an additional layer of assumptions, and therefore uncertainty, which needs to be examined and questioned. They are powerful tools to explore the potential consequences of a set of assumed changes but their output faces even more challenges in interpretation than the global models dealt with below.

Why is Climate Forecasting Hard?

Basic and well understood physical processes are enough to warn us that with increasing atmospheric greenhouse gases we should expect increasing surface temperatures, and that such increases in temperature will have a significant impact on many aspects of climate. These changes represent significant risks to global society and societies globally. The justification for very significant effort on climate change mitigation is clear.

Similarly, there is much understanding of climatic processes which can help guide decisions which are affected by the inevitable changes in climate over the coming decades to centuries. Some of this understanding is encapsulated within complex climate models and such models play a significant role in developing and refining our understanding. It would be foolish indeed to ignore such models and the information they contain. However, it would be similarly foolish to treat them as forecasting tools capable of providing probabilities which can be used as such in conventional decision making processes. The barriers to their use in this way are outlined below.

Extrapolation

The first and overarching barrier is the fact that climate change prediction is a problem of extrapolation. Unlike weather, and many other types of, forecasting the aim is to predict a state of the system which we have never before observed and which we will not observe before the forecasting system is of only historical interest. There is therefore no hope of verifying, or more appropriately confirming (Oreskes et al., 1994), the method. The onus is therefore on scientists to question as comprehensively as possible how the forecasting system could fail. This burden is far more substantial than in systems where confirmation is possible e.g. drug design, or where the research is principally of academic interest, e.g. astrophysics. It is by questioning how our predictions could be wrong that we learn best how to interpret and improve them.

Model Deficiencies

The second barrier is simply the quality of the models. Global Climate Models are at the same time fantastic achievements, tremendously powerful research tools, and significantly different to the real world they are taken to represent. There are model inadequacies (Stainforth et al., 2007a) in the sense that significant aspects of the system are not included e.g. the stratosphere, ice sheet dynamics, atmospheric chemistry etc. There are also model uncertainties (Stainforth et al., 2007a) in the sense that processes which are included can be poorly represented e.g. ENSO, the diurnal cycle of tropical precipitation etc. These deficiencies are not surprising but must be recognised if the models are to be used to inform us about the future of the real world system. Model uncertainty can to some extent be systematically explored, subject to computational resource constraints, but model inadequacy is not open to such systematic quantification. The impact of model inadequacies on the extrapolatory problem of climate prediction is however open to subjective judgement. This should be a critical part of any model based forecast. Communicating the significant assumptions made in relating the model response to the real world response is a key element in ensuring that scientific and computer model information is utilised appropriately.

However complex the model may be, it is still a highly simplified version of the real world. Furthermore, the processes of interest are complex non-linear interactions. It is therefore difficult, if not impossible, to say a priori which processes, at what scales, could lead to major regional or even global changes. This is not, however, a council of despair. In most fields of human endeavour we work with imperfect knowledge. This should not stop us using the best, relevant information we have. At the same time, acknowledging the problems can help us address them more effectively. This is the case here. The non-linear nature of the system suggests the need for greater emphasis on the exploration of the implications of sensitivity to initial conditions on the long term response of the system (Stainforth et al., 2007a). This is the so called "initial condition uncertainty (ICU)" described below. It is one of a number of types of uncertainty which are explored through ensembles of simulations.

Ensembles Exploring Model Uncertainty

The uncertainty in model based predictions of 21st century climate is explored using multiple simulations known as ensembles. Three types of uncertainty are explored with such ensembles (Stainforth et al, 2007a). First is external forcing or emissions uncertainty. This is dealt with through scenarios of greenhouse gas emissions or of atmospheric greenhouse gas concentrations, depending on whether or not the model includes a carbon cycle which can convert emissions into concentrations. Second is sensitivity to initial conditions, dealt with through multiple simulations with very slightly different initial values for prognostic variables. Third is the model uncertainty referred to above. This is handled either through ensembles of opportunity {similar simulations with multiple models which happen to exist worldwide e.g. CMIP III (Meehl et al., 2007)}, or through perturbed physics ensembles (Allen and Stainforth, 2002) where parameters within a model's parameterisation schemes are systematically changed for each simulation. These sources of uncertainty interact so in practice we need ensembles of ensembles of ensembles – so called grand ensembles (Stainforth et al., 2005).

A number of emissions scenarios exists (SRES) and more are being created to reflect political aspirations and the different impacts from different gases (e.g. Meinshaussen, 2009). These scenarios largely span the range of plausible anthropogenic emissions, though it is worth noting that CO_2 emissions between 2000 and 2006 were towards the upper levels of any scenario considered in 2000 (Raupach et al., 2007). Exploration of initial condition uncertainty is a key factor in weather forecasting but is relatively little explored on longer timescales; ensembles of 4 or less are common. Model uncertainty is explored either with international ensembles of opportunity, which involve around twenty models (Meehl et al., 2007), or with perturbed physics ensembles of single models which may achieve a few hundred simulations using in-house computing facilities (Murphy et al., 2007) or several tens of thousands with a distributed computing approach (Stainforth et al, 2004, Knight et al, 2007). Together multi-model ensembles of opportunity combined with perturbed physics ensembles provide an insight into the implications of model uncertainty. However, it must be remembered that global circulation models contain of the order of a hundred or so uncertain parameters in their parameterization schemes. Given the non-linear nature of the system, one would expect these parameters to have interactions which are important on regional and global scales. The computational challenge is therefore to explore a hundred dimensional space. In such a context even a few tens of thousands of simulations provides only limited exploration of uncertainty. A key challenge for climate science is to define the purpose and interpretation of such ensembles which can then inform how to prioritise simulations in parameter or multi-model space. A further challenge is to balance the exploration of the different forms of uncertainty.

Model Interpretation – Lack of Independence between Models

Given the existence of multi-model and perturbed physics ensembles, we would like to know how to use this information to inform impact and adaptation studies or, better still, practical decisions. The ultimate goal is often taken to be probability density functions (pdfs) of future climate. It is not clear that such a goal is necessary or appropriate (Hulme et al. 2009) and there is no obvious way to relate model diversity in such ensembles to real world probabilities due to the lack of independence between models or model versions (Stainforth et al., 2007a). This constitutes the third barrier discussed herein. It is this that makes the application of most standard statistical methodologies irrelevant in the analysis of such ensembles.

The core issue here is that we have no way of defining the space of all possible models or of measuring their "distance" from each other. The multiple models around the world share methods for representing the dynamical equations and for parameterizing sub-grid scale processes. They also use many of the same datasets to evaluate their model's ability to simulate the past. In perturbed physics ensembles there is no way a priori to know when a parameter has an important effect and when it is largely redundant. The resulting ensemble is in no way an independent sample of possible model versions. Indeed one might expect parametric redundancy and therefore there to be a significant bias towards model versions similar to the original unperturbed model (Stainforth et al., 2005). The consequence of this is that the areas of high model density in Figures 1, 2, and 3 can not be considered more likely simply as a consequence of the density of points.

Emulators and Model Space

As an aside it is worth noting that statistical emulators have been used to "fill-in" parameter space in an effort to overcome the subjectivity in selecting parameter values in the perturbed physics ensembles (Murphy et al. 2009, Rougier et al. 2009). This method adds complexity to the analysis but does not overcome the lack of independence problem because even the shape of model parameter space is the result of ad hoc decisions in the model formulation process (Stainforth et al., 2007a). Equally valid alternative decisions can change the shape of model parameter space and completely change the resulting probability distributions (Allen et al. 2006a, Allen et al. 2006b). This problem can be discussed in terms of both the importance and the arbitrariness of the prior sampling in a Bayesian formulation of the problem. Although not solving the problem, the added complexity of these approaches does create a barrier to informed discussion, interpretation and utilisation of the results.

Ensemble Interpretation: A Way Forward

Given the lack of model independence and the existence of model deficiencies, it is suggested that the way forward is to treat these ensembles as providing a "non-discountable envelope of possibilities" (Stainforth et al., 2007b). The concept here is that we acknowledge that all models have inadequacies, the significance of which must be handled in accompanying discussions of assumptions, and that they have model uncertainties which have only been partially explored in multi-model and perturbed physics ensembles. Yet to the extent that we do not know the impact of such deficiencies, the range of behaviour found within the ensembles should be considered uniformly plausible. That is to say that the information from current models suggests that we should not discount the possibility of the real world lying anywhere within the range (Stainforth et al., 2007b, Stainforth et al., 2007a, Stainforth et al., 2005). This does not imply that the region outside the range is discounted; it is simply a region about which we currently have no information from the models.

Metrics and Weighting

To go beyond the non-discountable envelope of possibilities requires us to be able to down-weight or rule out certain models or model versions. This represents the fourth and final barrier discussed herein. Complex climate models simulate many variables at timescales down to half an hour or less and many thousands of points around the earth's surface. It is therefore possible to use them to simulate the last century and to confront them with observations over that period. There are a number of difficulties in using this process to assign weights to models. First is that most observations were available to the model developers during the development and tuning process (Stainforth et al., 2007a). Failure to reproduce them is therefore indicative of a problem but success can not be treated as an indication of reliability. Second is that as a consequence of the non-linear nature of the system, we cannot choose to select or weight models based on some subset of variables in which we are interested. For instance, models which in the past simulate some variable over the eastern United States well but maybe not over some other region such as Alaska, should not be considered more reliable in providing information on how the eastern United States will change in the future. Models which are bad in some respects may contain feedbacks which are critical in other respects. The third difficulty is that these ensembles are analysed "in-sample" so there is a tendency to focus on models producing extreme results and look for the errors in such models. Because the models have been chosen after their results have been seen, such analyses can not be taken as reducing the uncertainty, although they can be used as a basis for defining constraints which could be applied to future ensembles. This problem is fundamentally a consequence of the fact that the ensembles are so computationally expensive that new ones can not be easily run. There are opportunities to make research progress on some of these issues.

Conclusions

These four barriers to the generation of probabilities for future climate on regional and local scales from General Circulation Models undermine several current approaches. But they do not undermine the fact that these models contain valuable information which can be useful in guiding societal decisions. By considering such barriers we can work more effectively towards better using the models, and associated scientific understanding, to guide climate change adaptation. Perturbed-physics ensembles should be designed to push out the bounds of the plausible. Integrating process understanding from climate physics and palaeo-climate observations are also likely to improve societal guidance. Designing robust metrics to judge when models have reached various stages of reliability will be valuable as we move forward, and integrating global climate understanding with local hydrological understanding could reap significant benefits. The opportunities to use complex climate models to guide societal decisions are substantial but the risk of their misuse is also substantial. The challenge is extracting and presenting relevant and robust information. Large uncertainty does not necessarily mean little information and non-discountable envelopes have the potential to help us make decisions which balance today's constraints with the need to minimise future risks and costs. The onus is on the scientific community to fully and openly discuss the challenges in this important field.

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Biography

David Stainforth is a Senior Research Fellow in the Grantham Research Institute. He is a physicist by training and has many years experience of climate modelling. While a researcher at Oxford University he co-founded and was chief scientist of the climateprediction.net project, the world's largest climate modelling experiment.

He has been both a NERC Research Fellow and a Tyndall Research Fellow at Oxford University. His current research interests focus on how we can extract robust and useful information about future climate, and climate related phenomena, from modelling experiments. This includes issues of how to design climate modelling experiments and how to link climate science to real-world decision making in such a way as to be of value to industry, policy makers and wider society.

Decision-Making Challenges with Nonstationarity

Engineering with Unreliable Frequency Estimates

Casey Brown, University of Massachusetts

Abstract

A new approach to identifying climate risks that would require adaptive management is being used on the Upper Great Lakes. The standard practice has been to simulate water related impacts expected under climate change by replacing current climate water supply with projected water supplies derived by downscaling the predicted changes in temperature and precipitation from General Circulation Models (GCMs) to transform the current hydrology. These simulations may provide a rough guess of what the future holds but are not particularly useful for decision making. Nor are they designed to be, although some decision is typically the endpoint of such efforts. For example, questions such as "when should we change our system" or "how much should we change" are difficult to address when no probability can be assigned to a particular climate change outcome used and there's no way to quantify the expected skill of GCM projections in the next century. The new approach presented here begins with stakeholders rather than climate models. Planners ask stakeholders and resource experts what water conditions they could cope with and which would require substantial policy or investment shifts. This is then formalized with a water resources systems model that relates changes in the physical climate conditions to performance metrics of interest to stakeholders. After these are established, hydrologists and climate scientists estimate the plausibility of the water conditions that exceed the coping thresholds, taking into account not only climate change but natural climate variability and stochastic variability observed with a stationary climate assumption. This paper reports on the early stages of a two year effort culminating in a Study Board recommendation to the International Joint Commission in the spring of 2012.

Problems with Conventional Climate Change Planning

Water managers need to consider the implications of climate change even if they are skeptical of climate projections because the impact could be great and because mitigative efforts might have to begin long before the effects on water systems are clear. Water resources planners have traditionally planned for uncertain future supply and demand by modeling system performance using forecasts of supply and demand and alternative system configurations. In the 20th Century, most supply forecasts were based on either the historical supply record or a statistical expansion of the historical record that included floods and droughts that were more severe than any recorded, but still consistent with the regional climate and geography. The widespread acceptance of this approach is characterized in "Stationarity is Dead: Wither Water Management?" (Milly et al, 2009):

Stationarity is a foundational concept that permeates training and practice in water engineering. It implies that any variable (e.g., annual streamflow, annual flood peak) has a time-invariant (or one-year periodic) probability density function (pdf) whose properties (mean, standard deviation, correlation structure, long-term persistence, etc.) can be estimated from the instrumental record. Under stationarity, pdf estimation errors are acknowledged, but have been assumed to be reducible by additional observations, more efficient estimators, or regional or paleo-hydrologic data. The pdfs, in turn, are used to evaluate and manage risks to water supplies, waterworks, and floodplains; annual global investment in water infrastructure exceeds $US 500 billion.

With the prospect of climate change, the future regional climate may be different from the past regional climate, and projections from GCM indicate the differences may be significant. As a result, planners need a different way to handle the uncertainty associated with future water supplies. The order of analysis in most water resources planning for climate change has been to start with climate change projections from global GCM, develop some practical strategy to use some subset of the large number of runs available due to time or budget constraints, downscale the projections to be suitable for use with a hydrology model and finally use the "climate change corrected" hydrology runs as input for a water resources system model to describe some possible future impacts. In an early example, the implications of future climate predictions derived from four GCM were used to evaluate the ability of the Columbia River reservoir system to meet regional water resources objectives (Hamlet and Lettenmaier, 1999). Almost all the work in such an analysis goes into converting regionalized and downscaled GCM outcomes into hydrologic datasets that can be used as input files for the existing impact models. Even in 2009 the most definitive Federal report on this issue, "Climate Change and Water Resources Management: A Federal Perspective" (Brekke, 2009) deals entirely with variations on this approach:

". . a general procedure might be used to connect climate information to planning assumptions:

- Survey contemporary climate projections that have been regionalized to the planning area and span the future planning horizon.
- Decide which projections, variables, and aspects to incorporate.
- Relate the retained information to natural conditions (for example, hydrology and ecosystems) and social conditions (for example, water demand drivers) that set up planning assumptions for supplies, demands, and constraints.

Milly and his co-authors of the "Whither Water Management" article suggest that traditional methods can still be used, but more work should be done to support the evolution of stationary world protocols.

This framework can be adapted to changing climate. Non-stationary hydrologic variables can be modeled stochastically to describe the temporal evolution of (at least) their means and variances, with estimates of uncertainty. Methods for estimating model parameters can be developed to integrate historical and paleo-hydrological measurements with differing projections of multiple climate models, of varying skill, driven by multiple climate-forcing scenarios.

Rapid flow of such climate-change information from the scientific realm to water managers will be critical for planning under nonstationarity, because the information base is likely to change rapidly as climate science advances during the coming decades. Optimal use of available climate information will require extensive training of (both current and future) hydrologists, engineers and managers in nonstationarity and uncertainty.

One might infer from this that these technical improvements will gradually restore a statistical characterization of the future, that with a little more research we will be able to calculate the odds of floods and droughts under climate change. For example, the "downscaling" (from global to river basin) approach used in the Columbia River study and more recent climate change studies, typically produces an estimate of how temperature and precipitation (and sometimes other climatic parameters) would differ at some future time. Recorded streamflow records can then be transformed into "climate change" streamflows using models that translate the change in temperature and precipitation to changes in flow. Because different emissions scenarios and GCMs produce different estimates of how greenhouse gas emissions into the atmosphere will affect temperature and precipitation, different GCM predictions are often used to describe uncertainty. The future may be considered to be somewhere inside the fence posts established by the different scenarios and models, although this is an assumption based on the unknown reliability of the GCM. Ultimately, this traditional approach as typically applied tends to be inconsistent with accepted use of GCM output in the climate community. For example, it is well known that the greater number of runs and models used increases the confidence that the projections represent the true range of uncertainty, yet most studies compromise on this number due to computational limitations. More important, the results of such expensive and time consuming efforts are rarely useful for decision making, precisely because these efforts have not been designed with decisions in mind.

From a decision making standpoint, the uncertainties of future climate are particularly challenging because we have available projections from sophisticated models yet no way to meaningfully assess the skill of those projections. Furthermore, the range of the projections is so wide the mean estimates are of little use. If we cannot assign probabilities to the projections we are faced with, then how do we know that we have probably framed the future? The problem has six distinct components.

First, estimates of future carbon emissions into the Earth's atmosphere based on socio-political scenarios over the next one hundred years drive all the GCMs. The socio-political scenarios have not been assigned probabilities because it was deemed too difficult to do so. The actual increase in atmospheric carbon will be a function of the global economy, climate treaties, and technological progress, and these drivers themselves are products of many volatile and unpredictable factors. Through about 2050 the differences between scenarios have little effect, relative to the difference between individual models, but after 2050 the differences are more pronounced. The second component is that the GCMs are models of reality that are not yet good enough to replicate current climate conditions at the spatial and temporal scales relevant to water resources planning and management (Brekke et al., 2008). At best, specific models emulate one variable, such as temperature, well but do not do as well on others, such as precipitation. None appear to do very well on variability measures, such as the serial correlation of annual precipitation. This is a critical failure for water planners because systems that can easily withstand six one year droughts interspersed with normal years may not withstand one six year drought. Furthermore, because each model run is a free integration constrained only by carbon emissions, their skill at producing year to year climate variables cannot be assessed. Only summary statistics, such as average climatology, standard deviation or serial correlation can be quantitatively evaluated, and those are of little use to the water sector where extremes and variability are of most importance.

The third issue is that the ability of GCMs to replicate current climate conditions is not a reliable indicator of their ability to predict future climate conditions (Murphy et al, 2004), so even if the models could pass the current climate test, it would not mean that they would serve the purpose they are put to in water studies, which is to provide a reasonable prediction of what future supplies will be. The fourth issue is that GCMs do not produce water supply datasets, so more assumptions and modeling are required to translate GCM outcomes (such as precipitation and temperature) to water supply inflows. There are already significant uncertainties in using rainfall-runoff models with observed input data, and here those errors are compounded by the unknowable error in the input file produced by climate models. In particular, the downscaling approaches typically employed provide no consideration of whether a GCM can actually reproduce the regional climate that is being downscaled, so "garbage in, garbage out" is a real risk. The fifth component is that these derived climate change supplies may lie outside the domain of supplies used to develop calibrate and validate empirical impact models. This is not a new problem – for instance, planners rarely are confident of estimates of flooding damages above the 500 year return period flood level – but the problem is bigger and more complex with climate change because of the potential for even greater departure from observed levels and because of the compounding effect of changing temperature and seasonal patterns. These compounding factors are often very important parts of the imagined future under climate change – the lack of water stored as snow in the mountains of the western United States, for example, or the reduction of ice cover on the Great Lakes. The sixth component is that there is convincing evidence of quasi-periodic climate variability from pre-industrialization and the GCMs do not replicate these phenomena. This is not surprising as most GCM are not even able to reproduce the El Nino/Southern Oscillation (ENSO). Natural climate variability brings its own forecasting issues; the impacts may occur much sooner than the effects of atmospheric carbon, but the quasi-periodic cycles are difficult to predict usefully. Whatever the effects of natural climate variability on water supply and demand, they will be superimposed on anthropogenic climate change.

The inescapable and inestimable uncertainty in GCM and downscaling-driven approach is not its only flaw. The method is time consuming, expensive and usually yields relatively short snippets of test data. In the recent IJC study of Lake Ontario regulation, the small dataset size results from the fact that downscaling required some transformation of recorded evaporation, and the evaporation records were short as measurements have only recently been started (IJC, 2006). The study employed a sophisticated downscaling approach using four GCM scenarios and a carefully correlated routing of supplies through all of the Great Lakes and the Ottawa River watershed. But the record length was only 29 years long, limited by the availability of historic data required to do the downscaling on the Ottawa River. These short records had two principal shortcomings; the supply sequences did not provide the variety of inflow conditions that would test regulation plans realistically and the duration of the dataset was too short to encompass the cycle lengths used in wetland models. As a result, these climate change scenarios were used only to test whether current plans would fail numerically under climate change – no effort was made to develop a climate change regulation plan.

Decision-scaling for Water Supply Planning

Most analysts consider the use of GCM-based hydrologic data, thinking that it at least is based on a scientific attempt to project the future based on our current understanding of the climate system. There's more comfort if multiple models of future water supply are used. But what comfort can a stakeholder take from knowing that we are prepared for one or three or even twenty specific future conditions which may or may not be likely? The alternative proposed here is to reverse the downscaling approach, asking first to identify the futures we are not prepared for and then asking if those futures are plausible. The concept of "plausibility" captures the notion that there's evidence that this future could happen based on our current understanding but it stops short of implying how likely that future is. The inverse direction of analysis addresses the problem of the paucity of observed test conditions generated by the downscaling methods versus what can be generated through stochastic simulation. Instead of hoping that a few scant downscaled datasets will reveal system vulnerabilities, we determine vulnerability independent of likelihood by asking resource experts and systematically exploring the climate sensitivities to develop a "climate response function" in terms of the metrics of interest.

We describe the inversion of the traditional approach to downscaling as "decision-scaling." Decision-scaling is the tailoring of climate information to be useful for decision making and can include downscaling when appropriate. The method is demonstrated through an application to domestic water supply reservoir performance using the design values for the water system of metropolitan Boston. A typical question that faces water managers, "Will climate change impact the system?" can be more specifically posed as "Will climate change require structural or management changes in order to preserve system reliability?" In this approach, reservoir inflows were estimated from regressions of precipitation and temperature. The reliability of the reservoir performance was described using an analytical approximation of a reservoir model that is applicable to reservoirs with over-year storage (Vogel et al., 2002). The reliability of the system was defined as a function of percent increase in average annual temperature, percent change in average annual precipitation and year to year streamflow autocorrelation. This was termed the "climate response function." Analysis showed that increases in temperature, decreases in precipitation, and increases in the serial correlation of flows would decrease reliability.

A plot of the climate response function in climate change space revealed a zone of potential climate changes that cause an unacceptable decrease in reliability which would require some adaptation. Temperature and precipitation projections were statistically downscaled from five models run under the three emissions scenarios that totaled over 100 GCM runs. Fewer than 5% of the runs indicated that reliability would be unacceptable. The decision scaling approach has clear advantages over the downscaling first approach. The primary advantage is that it replaces the ill-founded implication of "probability" with a defensible and quantified assessment of plausibility based on all the most recent runs of the GCMs. The computational efficiency of the climate response function allows a very large number of runs to be used to calculate metrics of interest because the GCMs are not used until the final step of the modeling procedure. This also eliminates the propagation of GCM uncertainties through the modeling chain which obscures the interpretation of results in traditional approaches. Most important, the GCM output has been tailored to provide useful information that addresses the decision described at the outset. Without a process designed to answer the relevant questions from the start, reaching useful information at the finish is coincidental at best. In this case, the water manager can say the water supply system will be reliable without modification under 95% of the future runs that the models currently project. The climate risk appears to be low. In addition, the decision scaling approach shifts the application of resources from more inconclusive climate modeling to efforts to understand and prepare for the problem.

Applying Decision Scaling to Adaptive Management of Upper Great Lakes Levels Regulation

In 2007, the International Joint Commission (IJC) established an independent study board composed of U.S. and Canadian members to review the operation of structures controlling Lake Superior outflows and to evaluate improvements to the operating rules and criteria governing the system. The Board is expected to publish recommendations in March 2012 for near term changes to the regulation plan as well as an adaptive management plan that could change the Lake Superior regulation plan or even initiate new regulation structures elsewhere in the Great Lakes. The study is known as the International Upper Great Lakes Study (IUGLS). In late 2009, the Board approved an adaptive management sub-study that will use decision-scaling. This paper is being written as those efforts are just getting underway; it summarizes the sub-study approach and speculates on how the study will play out and how it can be expected to differ from traditional studies of water management under climate change.

The IUGLS Adaptive Management Approach:

The approach uses an eight step process based on the new, decision scaling perspective.

1. Define system vulnerabilities
2. Develop risk scenarios
3. Define plausibility of risks
4. Develop Superior regulation strategies to address future risks
5. Evaluate new structures
6. Identify long-term monitoring and modeling needs
7. Conduct an institutional analysis
8. Develop and rank adaptive management plans.

The preparation of an Adaptive Management plan is part of a larger shared vision planning process that involves Great Lakes stakeholders in the development of the plan.

In Task l, resource experts will identify the vulnerabilities of the system to climate change and other unfamiliar conditions. Experts in ecosystems, hydropower, commercial shipping, municipal and industrial water and wastewater systems, coastal systems and recreational boating and tourism will delineate three water level zones: A (acceptable), B (significant negative impacts, but survivable) and C (intolerable without policy changes). A template for developing these zones has been developed by planners and sent to the resource experts.

Problematic scenarios will then be developed in Task 2 that combine the B-C water level zones with potential future economic and environmental shifts. The understanding of vulnerabilities will initially be defined in terms of the magnitude, frequency, duration and variability of water levels, and this in turn will be translated into water supplies that could produce those extreme water level regimes. But understanding vulnerabilities goes beyond just water supplies. The Great Lakes face a particularly uncertain future. It is not known with certainty what the next invasive species will be, or the next emerging toxic chemical. It is not certain how, or if, the Great Lakes manufacturing sector hit hard by the 2008 economic downturn will recover, or whether society will be successful in reducing CO_2 emissions. There are numerous economic and environmental challenges that face the region that could have implications both on how vulnerable various interests may be to a changing climate regime, and on how management decisions may be made in the future. For example, Great Lakes commercial shipping has declined from the peak levels of the 1970s and was down by a third in 2009, a bad year, but there have been several significant think tank reports touting the possibility of greatly expanded shipping. A strong commercial navigation industry would certainly be more capable of dealing with periods of low water levels better than a deteriorating industry. Similarly, should Asian Carp, a large fish brought into clean catfish farms in the southern United States and moving up the Mississippi River and now close to entering Lake Michigan despite redundant electrical fences designed to keep them out succeed in populating the Great Lakes, fishery experts feel they will destroy the native fish populations. This and other unforeseen species changes would certainly have implications for how adaptable the environment may be to future climate changes, and/or to the management actions taken. Experts will develop an array of these economic and environmental scenarios, which will be supplemented by responses to formal queries to the Study Board members and key members of the Public Interest Advisory Group.

In Task 3, the plausibility of these scenarios will be evaluated. The term “plausibility” is not used as a synonym for “probability”. It is used to acknowledge that GCM runs do not represent the true probabilities associated with future outcomes, yet do describe possible futures with some fidelity that are consistent with our current understanding of the earth’s climate system. Furthermore, we use the implicit assumption that model consensus is indicative of skill and the good practice of using GCM output at appropriate temporal and spatial scales. Suppose for example that in Task 1 commercial shippers agreed that levels 25 cm below some previous record low levels would constitute a Zone C condition because water levels this low would almost certainly lead to the permanent loss of traffic.

The observed record low monthly average water level on Lake Superior is 182.73 m (IGLD 1985) occurred in April 1926. One climate change scenario representing the warmer, drier edge of GCM predictions showed that levels would be about 10 cm lower than that. The plausibility of this condition can be estimated according to a large range of GCM runs using a climate response function. Locally, these impacts would either be mitigated or aggravated by projected changes in land elevation as the earth’s surface around the Great Lakes continues to respond to the weight removed because the glaciers that covered this area melted away about 12,000 years ago.

Ultimately, the relative plausibility of a Zone C condition will help define the level of effort applied to averting it.

Possible Adaptive Management Strategies

Tasks 4 and 5 address plan formulation and evaluation for two categories of alternatives; changes to the rules governing releases from Lake Superior (Task 4) and the construction of new regulation structures with new operating rules (Task 5). It is too early to say how these alternatives will be structured exactly, but planners have sketched out a starting point for each that will be refined in a series of practice decisions by the Study Board.

In this initial perspective, adaptive changes to the regulation of Lake Superior could include modest and even reversible adjustments to the rules to achieve the same objectives, or later, more extreme adjustments that would reflect a change in regulation objectives. In each case, a trigger for shifting from one plan to another would be designed and evaluated, and there would be a plan to monitor the data needed to identify the trigger points and later the success of the management changes made. There might be recommended research to reduce the risks inherent in the original design, too.

As an example of modest adjustments, an alternative named "Plan122" (a plan developed as part of the 1993 Levels Reference Study), provides economic benefits by raising the lowest levels of Lakes Michigan and Huron, where about 40 percent of the Great Lakes basin population reside, while also lowering Lake Superior, home to only about 2 percent of the basin population (Dunning, 2009). One way that Plan 122 differs from the current plan (called 1977A) is that it bounds the lowest Lake Superior releases. When these plans are simulated using a 50,000 year stochastically generated, current climate water supply series, the minimum Lake Superior release from Plan 122 is 1,556 m3/s while the minimum for 1977A is 1,039 m3/s, a reduction of a third. Plan 122 does not produce drastically lower Lake Superior levels when simulated using historic levels, but it produces a much different distribution of levels from 1977A when simulated using the stochastic supplies. An adaptive management plan might identify a set of triggering conditions that would eliminate Plan 122 restrictions on minimum releases and then apply them again when a different set of triggering conditions were met. These sorts of adaptations are similar to any conditional rule set except that the triggering climate or other conditions would suggest a climate regime shift under which the current regulations were suboptimal and would be based on hypotheses about persistence in Great Lakes levels. In this case the objectives of the plan remain the same, but the specific rules are conditional on a set of triggers.

An example of a more pronounced adaptation is a change in regulation plan objectives. The regulation plan must honor the International Boundary Waters Treaty of 1909 between Canada and the United States, so one objective that will not change is that regulation cannot leave users worse off than they were without regulation. (This is a simple explanation of a concept that is subject to judicial refinement). But a notable objective of Plan 1977A that is not guaranteed by the treaty is that it tries (with constraints) to "balance" Lake Superior and Lake Michigan-Huron levels, adjusting releases to keep the lakes the same number of standard deviations from their mean levels. If climate change were to lower Great Lakes levels by a few feet, as some models have predicted, then the adaptive management plan, through the monitoring and assessment of climate and impact triggers, might identify future conditions where a balancing objective no longer seems appropriate because it would tend to lower Lake Superior quite a bit without helping to raise Michigan-Huron levels much. A new objective might be used, for example, to keep levels on Lake Superior as close as possible to historic ranges, preserving connectivity between the lake and its feeder streams necessary for fish access and possibly minimizing significant changes to the biotic community and ecosystem functions of that lake.

Task 5 is to develop multi-lake regulation operating rules for new hypothetical structures in the St. Clair and/or Niagara rivers that, in combination with the St Marys River control structures (or some revised structures) provide a variety of ways to manage levels throughout the Great Lakes that meet a set of hydrologic objectives. While recommendations for additional structures might seem incredible given how unusual it is to build major dams in North America, if climate change were to lower lake levels as much as depicted by some GCM projections, this may be the only way to keep water levels near twentieth century levels and avoid substantial economic and environmental damages. Even the form of this recommendation is not clear yet, but an assessment of hypothetical structures will, at a minimum, determine some possible means of influencing levels and flows and could lead to recommendations for conditional exploration of new structures should there be a clear indication that such structures have the potential to effectively meet established objectives.

Implementation

Adaptive management is praised more than used. Carl Walters, who along with C.S. Holling is credited with creating the concept of adaptive management, articulated this problem and the causes for it in a 2007 paper:

There have now been upwards of 100 case studies where attempts were made to apply adaptive management to issues ranging from restoration of endangered desert fish species to protection of the Great Barrier Reef. Most of these cases have been failures in the sense that no experimental management program was ever implemented, and there have been serious problems with monitoring programs in the handful of cases where an experimental plan was implemented. Most of the failures can be traced to three main institutional problems: i) lack of management resources for the expanded monitoring needed to carry out large-scale experiments; ii) unwillingness by decision makers to admit and embrace uncertainty in making policy choices; and iii) lack of leadership in the form of individuals willing to do all the hard work needed to plan and implement new and complex management programs.

Of the three main causes of implementation failure described above, easily the most important has been lack of leadership to carry out the complicated administrative steps involved in moving a new management vision into actual field practice.

The IUGLS study board is committed to implementing an adaptive management plan. The institutional study in Task 7 will investigate how the plan written in Task 8 will be funded, who would be responsible for each element of the plan, and how approvals for the plan would be secured. This will not guarantee that adaptive management will occur even if these tasks are done well. The study board will recommend adaptive management to the IJC, and the common assumption is that a number of U.S. and Canadian agencies would have to agree to carry out different elements of the plan. But the adaptive management element of IUGLS has been designed to improve the odds of successful implementation.

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Biography

Research Interests: Hydroclimatologic variability and change, Climate risk management in infrastructure systems, Water-climate and economic development, Sustainable water resources planning and management

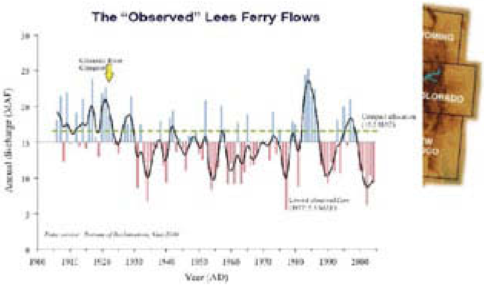
Education: Ph.D., Harvard University, 2004., M.S., University of Massachusetts, 1994., B.S., University of Notre Dame, 1993.

Professional Experience: Assistant Professor, Department of Civil and Environmental Engineering, University of Massachusetts Amherst, 2008-present, Adjunct Associate Research Scientist, IRI, Columbia University, 2008-present, Adjunct Assistant Professor, Dept. of Earth & Environmental Science, Columbia University, 2007-2008, Associate Research Scientist, IRI for Climate and Society, Columbia University, 2006-2008

The Colorado River Compact (1922)

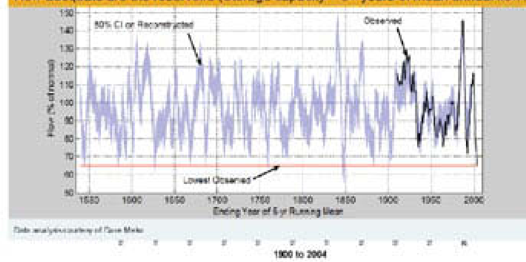
Low flow in the Colorado River Basin spurs water shortage discussion among seven states

2005 Headline



Hydrologic/Climatic Variability

How should these long periods of climatic departures be managed?
How adequate are the reservoirs (Storage capacity = 5+ years of mean annual flow?

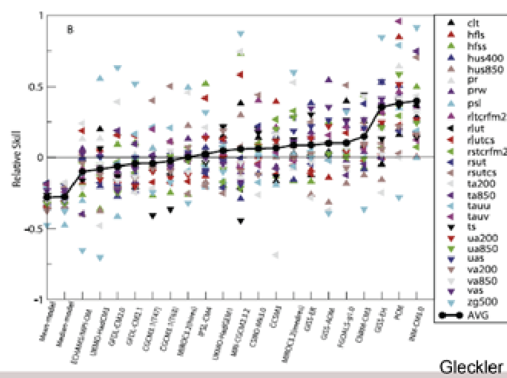


From Eric Kuhn, 2005

Limitations of GCM for WatRes P&M

- Significant, irreducible uncertainty associated with climate change projections
- Model error and inherent uncertainty require ensembling
  - Multi run (initial conditions) for inherent uncertainty
  - Multi model to account for model errors
- Are mean projections useful?
- GCMs not designed for Adaptation, not easy to evaluate
  - Coarse resolution grid cells (100s of kms)
  - Results applicable at the "continental scale" and seasonal or annual values - IPCC AR4
  - Results have biases and other errors, e.g. daily precip.
- Errors propagate through each modeling step
- Probabilistic approaches computationally expensive

Model Errors by Variable



Gleckler et al., 2007

Decision Framework

Is action necessary for adaptation to climate change?

Compare Expected Net Benefits of Action vs No Action

Expectation based on the probability of a climate change that requires action

Two Decision Frames:

- One Shot: E.g., infrastructure
- Sequential: E.g. Adaptive Management, update with observations

Decision:

Is action necessary for adaptation to climate change?

Compare Expected Net Benefits of Action vs No Action

Expectation based on the probability of a climate change that requires action

➡ Based on the "Adaptive Capacity" of the system

1. Climate Risk Assessment and Management

Static Design: Reduce uncertainties of future climate conditions and guess best

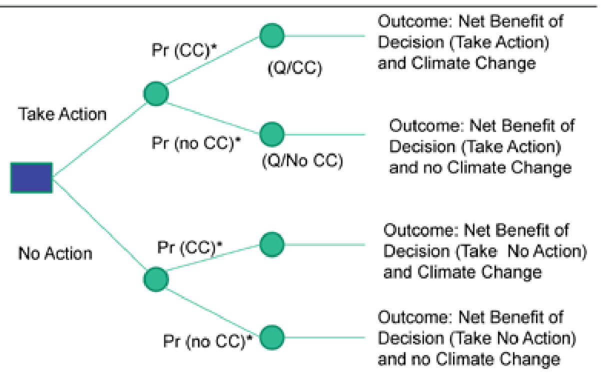
Dynamic Design: Probabilistic estimate of risks and design strategies to manage them all

1. How is the system (or decision) sensitive to climate?
2. Based on the information needed, can climate information be tailored to assist the decision?
   - Potentially at multiple timescales
3. Given the uncertainties, what are the residual risks of a given decision and how can they be managed?
   - What are the implications of being wrong?

Decision-based Approaches Needed

- Climate Risk Assessment: Can we design a decision process for wat res that is appropriate for the limitations of future projections?
  - Decision scaling
- Climate Risk Management: Can we innovate water management strategies that are resilient to an uncertain future?
  - Flood risk reduction
  - Reservoir operations
  - Demand management
  - Ecosystem management

Bayesian Decision Tree



* CC defined according to decision; Pr(CC) via decision-scaling

Decision-based Approach

$$\sum_{i=CCtype} NB(Decision\ \ X|CCtype_i)\Pr(CCtype_i)$$

? ?

$$\Pr(CCtype_i) = \sum_i \Pr(CCtype_i|\overline{CCtype_i})\Pr(\overline{CCtype_i})$$

- Appropriate Scales
- Model Consensus
- Risk Management

Decision Scaling

Downscaling = mapping GCM output to smaller grids.

<u>Decision scaling</u> = Tailoring climate information to assist decision making

- **Premise: Since GCMs are limited in their ability to provide information, begin by specifying what is needed for the decision**
- **Inverse Modeling approach – begins with the system or decision model to derive a "climate response function"**
  - **Model Order Reduction techniques**

Define climate types:

- Climate Type I: Adaptive Capacity sufficient
  - "Comfort Zone"
- Climate Type II: Adaptive capacity exceeded
  - "Beyond coping range"

- How are they defined? "**Climate Response Function"**
- **Decision:**

$$\sum_{i=CCtype} NB(Decision\ \ X|CCtype_i)\Pr(CCtype_i)$$

System Model

Tailored Climate Information

Climate Risk Case I – Over Year Storage Reservoir

- Eastern Metropolitan area
- Water supply for 2.2 M
- Dominated by carry-over storage

with M. Laverty, Y. Ghile

Climate Risk Assessment: 1-shot decision

- QUESTION: Will climate change impact the system?
- REFRAMED QUESTION: Will CC cause a Reliability change that requires structural or management changes?

STEP 1: Identify sensitivity of Reliability to climate changes. (System Model)

STEP 2: Estimate probability of "problematic" changes in climate. (Tailored Climate Information)

STEP 3: Develop strategies that address the risks. (Climate Risk Management)

System and Decision Model

Decision Model: Climate Type 1 = Reliability > 95%
Climate Type 2 = Reliability < 95%

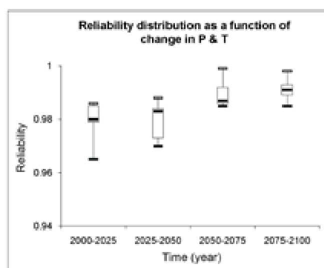
Reliability as a function of reservoir inflow, demand, and variability: (Model Order Reduction)

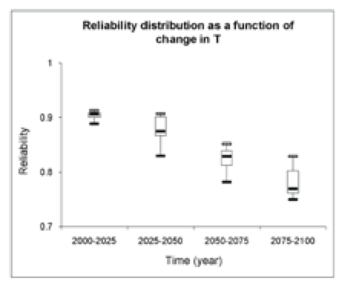
S = reservoir storage
m = inflow/demand
ρ = serial correlation of annual inflow
σ = standard deviation of annual inflow
t_q = standard normal variable at percentile q

$$t_q = \sqrt{\frac{4Sm}{\sigma}\left[\frac{1-\rho}{1+\rho}\right]} \Rightarrow \text{"Climate Response Function"}$$

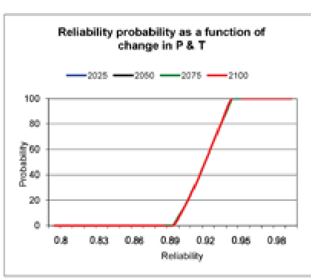
Vogel et al. (1995) and Vogel and McMahon (1996)

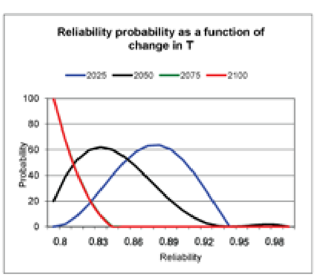
Probabilistic Assessment of MWRA reliability based on GCM output





Probability of MWRA reliability based on GCM output



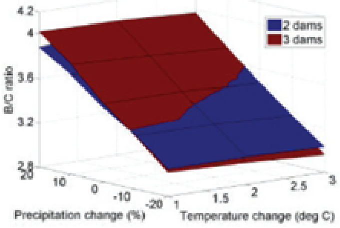


Results: Probabilistic Climate Risk Assessment

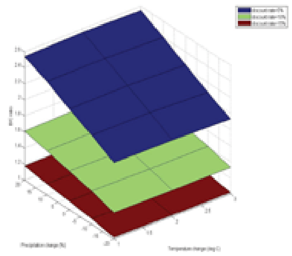
- Take Action if Reliability < 95%
- Based on changes in Precip and Temp
  - Probability (Reliability < 95%) = 5%
- Based on Temp only
  - Probability (Reliability < 95%) = 60% in 2025
  - Probability = 90% in 2050
- Next Step
  - Identify and address the residual risk
  - GCMs do not reproduce serial correlation, future = ?

Water Resources Planning – Does Climate Matter?

Blue Nile – 2 or 3 Dams in Ethiopia?



2 Dams – which discount rate?



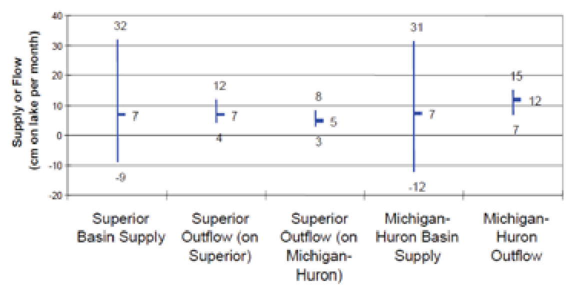
Block and Brown, 2009

Case 2: Dynamic Management

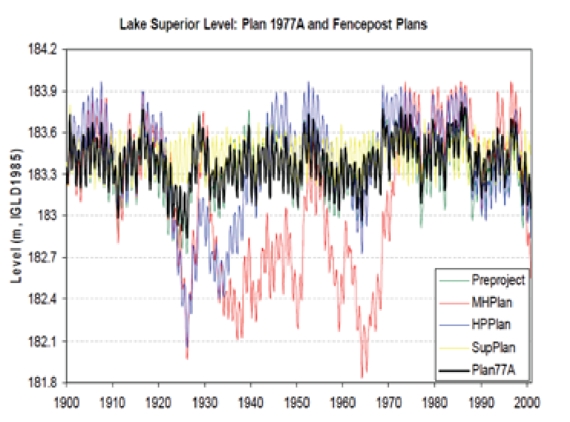
Regulate Lake to meet multiple objectives while accounting for climate change:

- Ecosystem Services
- Navigation
- Recreation
- Hydroelectricity Production

Variability of Water Supplies and Outflows



Lake Ontario: Outflow range = 59 cm to 135 cm /month
Total Supply = 51 to 158 cm /month



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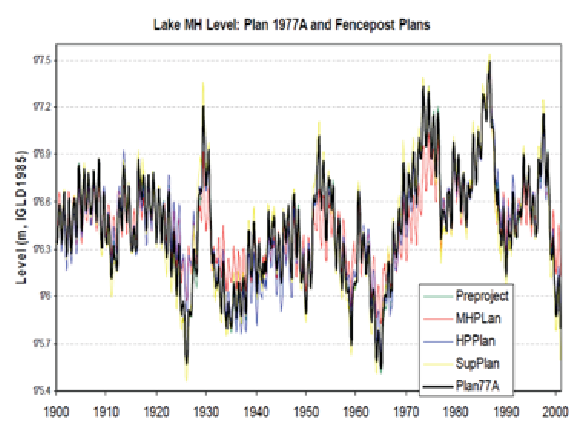

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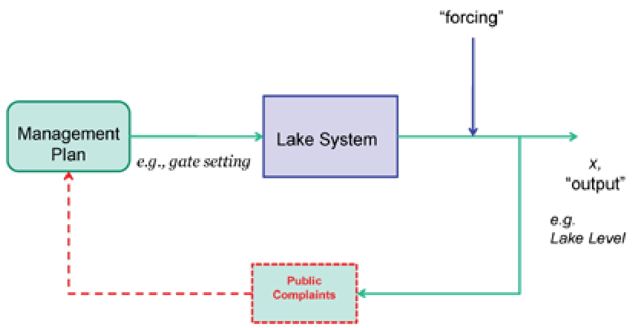
Current Management of Lake Superior



x^* = desired output

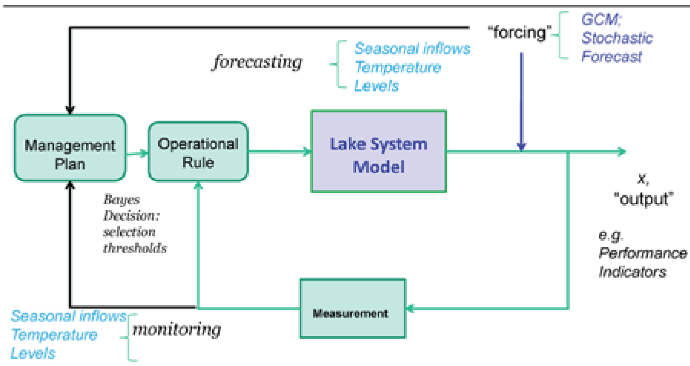
If $x_t - x^*$ > *Target* and Complaints > *Tolerance* then Study for new Management Plan

After Anderies et al., 2007 (PNAS)

Static vs Dynamic Management

- Static Design Paradigm
  - Project the future and reduce uncertainty
  - Select the "optimal" plan given best estimate of future conditions
- Dynamic Design and Operations
  - Future is highly uncertain and uncertainty is irreducible
  - Our best estimate will be wrong
  - Select the "optimal" plan for several plausible futures
  - Identify the conditions for switching between plans
    - E.g., current lake level and lake level forecast
  - Identify and manage the residual risks (non-optimal plan for given conditions)

Dynamic Management



After Anderies et al., 2007 (PNAS)

Climate Info. for Adaptive Management

Sequential Decision w/ updated Probability of climate change given the observations:

$$\sum_{i=CCtype} NB(Decision\ X|CCtype_i)\Pr(CCtype_i|observations)$$

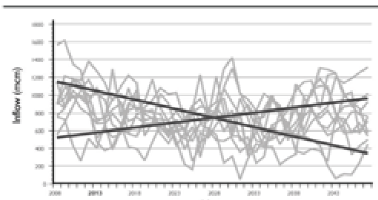
System Model

Tailored Climate Information

Tailored Climate Information:

$$\Pr(CCtype_i|observations) = \Pr(observations|CCtype_i)\Pr(CCtype_i)$$

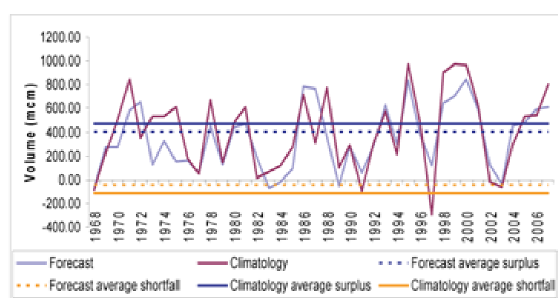
Trend vs. Variability: Manila (Ph) Water Supply



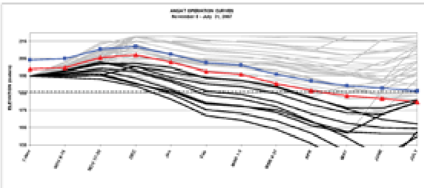
Shown:
- - 20% Trend
- Superimposed Multidecadal variability
- Observed Interannual Variability

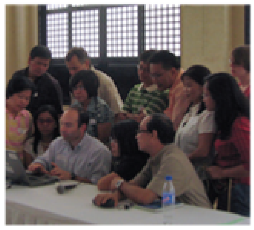
Scenario	Cumulative deficit statistic (mcm)	Average reliability first 10 years	Average reliability last 10 years
No trend and no multidecadal signal	59	64%	65%
Trend of +20% and no multidecadal signal	33	68%	82%
Trend of -20% and no multidecadal signal	94	65%	49%
Trend of +20% with multidecadal signal	64	70%	79%
Trend of -20% with multidecadal signal	198	65%	46%
No trend, but with multidecadal signal	145	64%	62%

Potential Value of Seasonal Forecasts of Inflow



Seasonal/Interannual Forecasts for Water Management





- Value in optimal rational decision making does not equal value to decision maker
- Risk aversion discounts benefits of forecast use and magnifies costs of unlikely events
- Must manage the residual risk of climate information use in order to benefit

Flood Risk Management – more than p(s)

$$\min Z = \sum \text{permanent measures} \times \text{cost} + \int (\text{option measures} \times \text{costs} + \text{damages})ds$$

Lund (2002):

$$\sum_{i=1}^{m} c_{Pi}(X_{Pi}) + \int_{0}^{\infty} p(s)\left[\sum_{i=1}^{j} c_{Oj}(X_{Oj}(s),s) + D(\vec{X}_P, \vec{X}_O(s))\right] ds$$

where

s = flood stage

X_P = Permanent flood control measure

c_P, c_O = costs of measures

D = damage function based on flood stage, flood control measures

p(s) = probability of given flood stage

X_O = option flood control measure

Does nonstationarity matter? We don't know!

Peak Flow Exceedance Probability → Damage Function → "Optimal" Flood Risk Reduction Plan → Actual Flood Risk Reduction Decision

"Nonstationarity"

"the wicked"

Rittel and Webber (1973)

Robust Decision Making

Robert Lempert, RAND

Abstract

The IPCC's Fourth Assessment report concludes that most climate-related decisions are best addressed with an iterative risk management framework. Such a framework defines risk as the impact of some adverse event multiplied by the probability of its occurrence and recognizes that any risk management process does not rely a single set of judgments, but rather a cycle of ongoing assessment, action, reassessment, and response that will continue over time. While water managers have long-practiced such an iterative risk management approach, the nonstationarity of future climate presents new challenges for its implementation. In particular, replacing climate distributions derived from recent historical records with distributions or scenarios derived from climate models or paleoclimate data highlights the imprecision in any such estimates. Water managers face not only the normative challenge of how to choose the best plan given deeply uncertain estimates of future climate, but also the organizational/political challenge of justifying their choices to diverse constituencies at a time when significant resource constraints and many competing demands make it difficult to give high priority to any but the most pressing (and unambiguous) needs.

This talk will describe how robust decision making (RDM) can help water resource managers to implement an iterative risk management under conditions of climate nonstationarity. RDM is a new quantitative decision analytic framework designed to support decision making under conditions of deep uncertainty, that is, conditions where the parties to the decision do not know or cannot agree on the system model that relates actions to consequences or the prior probability distributions on the uncertain input parameters to those model(s).

RDM rests on three key concepts that differentiate it from the traditional subjective expected utility decision framework: multiple views of the future, a robustness criterion, and reversing the order of traditional decision analysis by conducting an iterative process based on a vulnerability-and-response-option rather than a predict-then-act decision framework. These features allow RDM to combine some of the best features of traditional risk management, its ability to quantitatively compare tradeoffs among alternative strategies in the presence of uncertainty, with the cognitive benefits of traditional scenario-based planning, which can help diverse groups agree on actions without agreeing on expectations about the future. In particular:

First, RDM characterizes uncertainty with multiple views of the future. In some cases these multiple views will be represented by multiple future states of the world. More generally, RDM incorporates probabilistic information by using ranges or, more formally, sets of plausible probability distributions to describe deep uncertainty. Such sets of distributions help characterize imprecise probabilistic information.

Second, RDM uses robustness rather than optimality as a criterion to assess alternative policies. Robust strategies are often adaptive, that is, they are designed to evolve over time in response to new information. Such robust adaptive strategies are designed to work well over a wide range of plausible scenarios. Thus, they are an appropriate choice when confronting deeply uncertain information about the future. Such strategies also allow groups of decision makers reach agreement on near-term actions even when they disagree about long-term expectations.

Third, RDM employs a vulnerability-and-response-option analysis framework to characterize uncertainty and to help identify and evaluate robust strategies. This structuring of the decision problem is a key feature of RDM. The traditional decision analytic approach follows what we have called a predict-then-act approach that first characterizes uncertainty about the future, and then uses this characterization to rank the desirability of alternative decision options. Importantly, this approach characterizes uncertainty without reference to the alternative options. In contrast, RDM characterizes

uncertainty in the context of a particular decision. That is, the method identifies those combinations of uncertainties most important to the choice among alternative options and describes the set of beliefs about the uncertain state of the world that are consistent with choosing one option over another. This ordering provides two key benefits. It enables the use of statistical techniques that can succinctly summarize highly complicated, deeply uncertain information about the future. It also provides cognitive benefits in decision support applications, allowing stakeholders to understand the key assumptions underlying alternative options before committing themselves to believing those assumptions.

RDM has been used to support a wide range of climate-related decisions, in particular helping water resource managers incorporate climate-change into their long-range plans. This talk will describe the RDM approach, show an example application for Southern California's Inland Empire Utilities Agency, and describe evaluations that measure RDM's impacts with decision makers.

Introduction

Greetings. I am Robert Lempert, a senior scientist at RAND and Director of RAND's Frederick S. Pardee Center for Longer Range Global Policy and the Future Human Condition.

Today, I am going to talk about Robust Decision Making (or RDM), a new quantitative, decision analytic approach for supporting decisions under conditions of what we call deep uncertainty. You will see many similarities to concepts from other talks at this workshop, including Mike Dettinger's descriptions of the uncertainty in climate models, the decision support approach discussed by Casey Brown, and Marc Waage's talk about the planning process at Denver Water. The work I will show encompasses the efforts of many of my RAND colleagues, including David Groves, Steven Popper, and Steve Bankes.

This workshop focuses on nonstationarity, a topic that has inspired much discussion over the last two days. Rather than debate whether nonstationarity exists as an intrinsic concept, I prefer to note that the word "stationarity" provides a good description of a key assumption water planners currently make— that one can use historical climate records as a surrogate for future climate projections in water management planning processes. It is important to note this assumption, because many agencies will most likely need to relax it in the future. When water managers begin to plan using statistics of future climate based on projections—rather than just use statistics that replicate recent history—they will face two important challenges. First, they will need to summarize incomplete information from new, fast-moving, and potentially irreducibly uncertain science. Second, they will need to justify their analytic choices to diverse constituencies, many of whom may object to implications of some particular choices.

This workshop discussed the first challenge a great deal. Water managers must determine how to best summarize incomplete scientific information about future climate. Climate models do an increasingly good job of explaining the changes we have seen to date. But looking forward, there will continue to be irreducible uncertainties. As Mike Dettinger suggested in his talk at this workshop, many interesting questions are always going to be out of sample, that is, based on models projecting future climate conditions outside the bounds of experience found in historical data.

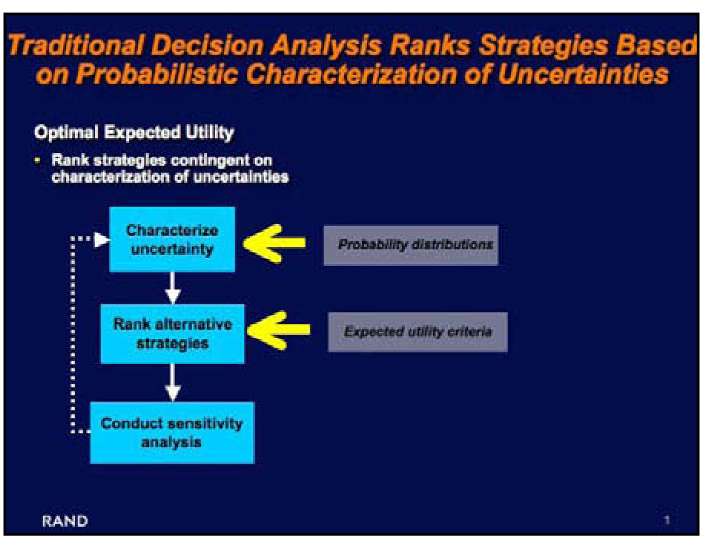


Figure 1. Steps of traditional decision analysis.

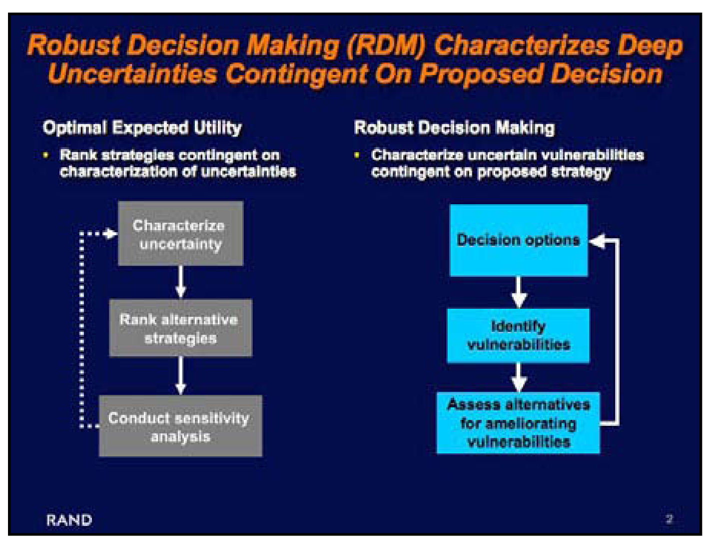


Figure 2. Steps of Robust Decision Making analysis.

This workshop has not discussed the second challenge as much. But those running a resource management agency face a significant challenge in choosing an analytic forecasting method to replace their current assumptions about stationarity. Not only do managers need to satisfy themselves that they have found a good solution, their constituents will soon realize that different analytic methods may have different implications for, say, how their tax dollars are allocated or how much they are charged for water at the meter. These constituents may then develop their own opinions on which methods they like and do not like and may begin to challenge the agency managers on their choices.

Choosing the best available methods for forecasting future climate is certainly important. But even the best methods may not overcome the challenges of irreducible uncertainty and stakeholders' responses to it. Rather, the solution may require rethinking how we use uncertain information to make decisions. This is the conclusion of a recent report by the U.S. Climate Change Science Program, of which I was one of the authors. This report (CCSP 2009), Best Practice Approaches for Characterizing, Communicating, and Incorporating Scientific Uncertainty in Climate Decision Making, argued that there are limits on how applicable and useful classic decision analysis—which seeks optimal strategies based on probabilistic forecasts—is for climate-related problems and that seeking robust, as opposed to optimal strategies, may be the preferable approach.

In this talk, I will expand on this theme by introducing the concept of Robust Decision Making. I will lay out the approach and then describe an example application for a water management agency. I will close by describing work we have done that evaluates the impact that these approaches have on the ability of water agencies to make better decisions.

There are a rich array of traditional analytic methods to help manage risk and improve decisions (see, for instance, Morgan and Henrion, 1990). These methods follow a series of steps we call predict-then-act, as shown in Figure 1, with the goal of determining the best decision strategy. First, the analysis describes what we know and do not know about the future—often using probabilities. Next, the analysis uses these predictions of the future to rank alternative strategies. Finally, the analysis might conclude by conducting sensitivity analysis.

These traditional predict-then-act approaches prove extraordinarily useful for a wide range of decision challenges. I often comment that you would never get on an airplane where the people who flew it and designed it were not very skilled with the predict-then-act approach. But in some situations, decision makers are confronted with conditions of what we call deep uncertainty, which is where the parties to the decision do not know or cannot agree on the system model that relates actions to consequences or the probability distributions over the uncertain inputs to the system model(s) (Lempert, Popper, and Bankes, 2003).

Under such conditions of deep uncertainty, decisions can go awry if decision makers assume they face well-characterized risks (Lempert et al., 2004). First, decision makers may feel significant pressure to underestimate the uncertainties, because admitting the full extent of them will overly complicate the analysis. Second, assuming well-characterized risks may contribute to gridlock, because it becomes easy for adversaries to attack any analysis whose results they oppose by pointing out, correctly, that its predictions are likely to prove wrong. Finally, decision makers may have information that is useful for making better decisions, even though it is not useful for making better predictions.

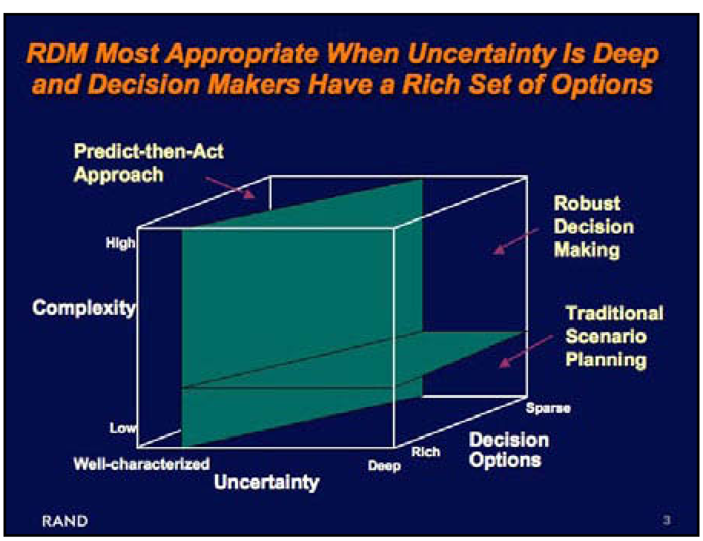


Figure 3. Conditions where Robust Decision Making often proves most useful approach.

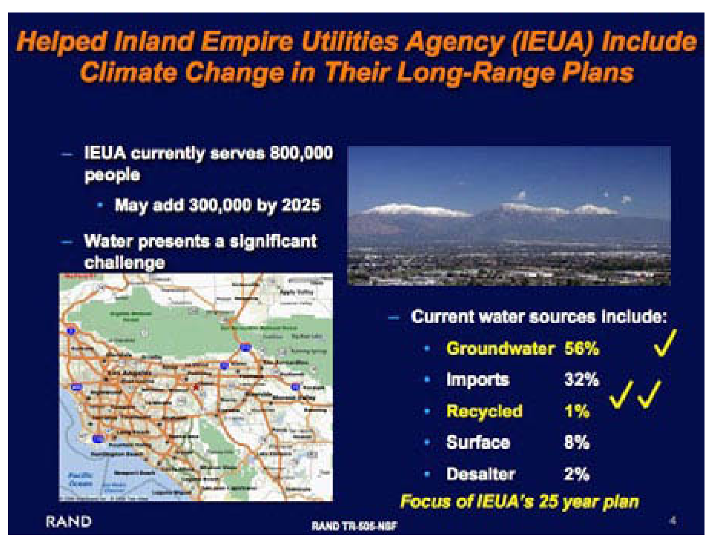


Figure 4. Location, current water sources, and current water management plan for Inland Empire Utilities Agency.

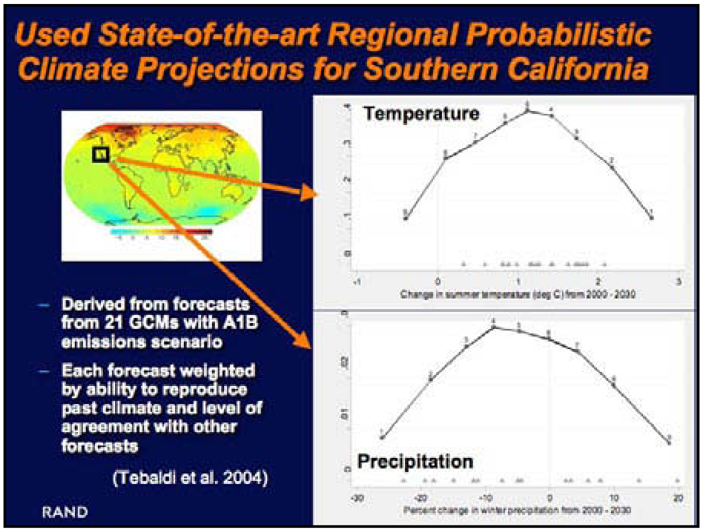


Figure 5. Regional climate information used in this analysis.

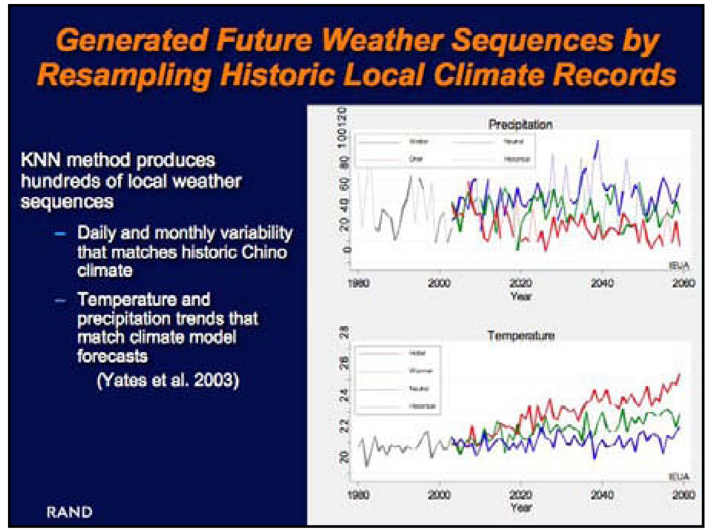


Figure 6. Example future weather sequences used in this analysis.

Robust decision making is designed to address these challenges of supporting decisions under conditions of deep uncertainty (Figure 2).

As shown in the figure, the approach inverts the order of traditional predict-then-act analyses. Rather than starting with the uncertainties, RDM begins with one or more decision options under consideration. It then uses simulation models and data to evaluate the conditions where these policies will succeed or fail. That is, RDM characterizes uncertainty by identifying the vulnerabilities of proposed strategies.

Once the analysis has identified vulnerabilities, it can help decision makers assess how to respond. RDM can help identify modifications or alternatives to the decision options that can address these vulnerabilities. The RDM analysis then constructs trade-off curves that can help decision makers decide whether they want to adopt any of these new decision alternatives.

This RDM approach provides several key advantages. First, it helps parties to a decision reach consensus on near-term actions, even when they disagree about the best policy choices and on expectations about the future, because a robust strategy works reasonably well across a wide range of such expectations. Second, the approach can help reduce the potential for overconfidence and surprise, because it provides a systematic and non-threatening way to introduce stressing and potentially surprising cases into the analysis (Lempert and Popper, 2005; Lempert, 2007). Finally, the approach provides a systematic means to introduce imprecise probabilistic information into a systematic decision framework (Lempert and Collins, 2007).

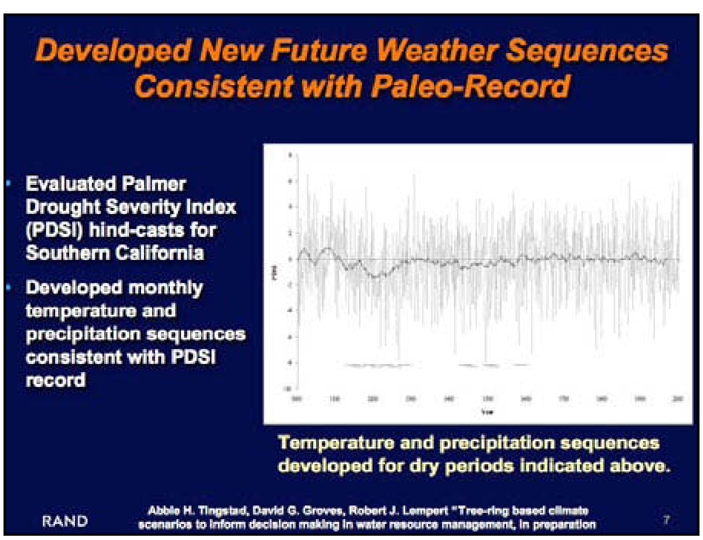


Figure 7. Paleoclimate information relevant to the analysis.

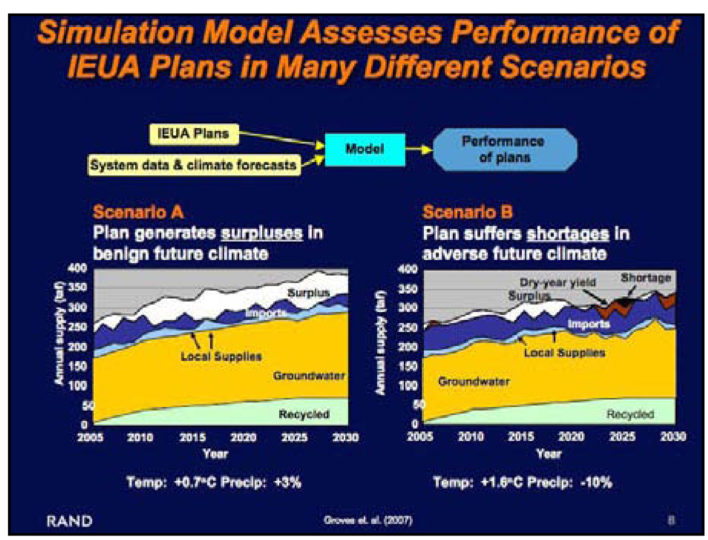


Figure 8. Initial scenarios considered.

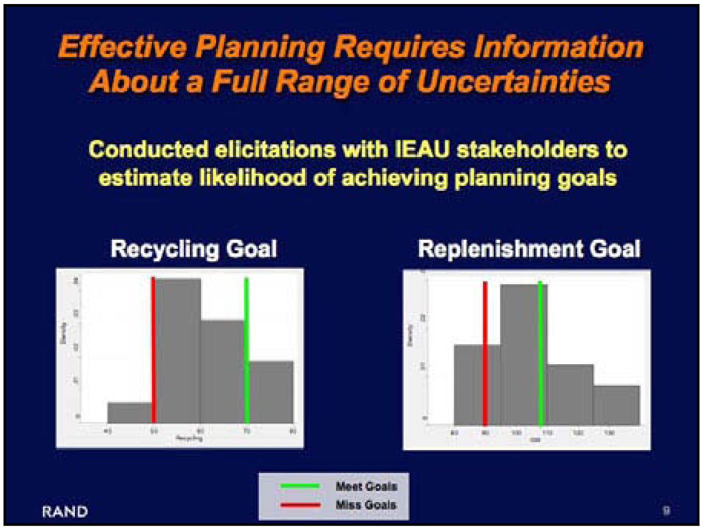


Figure 9. Estimates of the uncertainty in IEUA's ability to implement its plan.

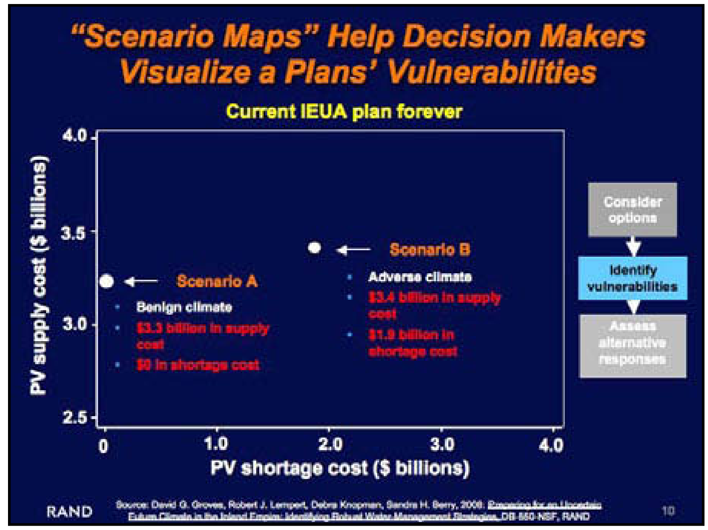


Figure 10. IEUA scenario map with two scenarios.

The concepts underlying RDM are not new. In fact, good decision makers have always identified and responded to vulnerabilities in their plans. For the first time, however, RDM harnesses advanced computer power to help decision makers directly implement these steps.

Before moving on to our example application, it is important to define the conditions under which RDM may prove most useful. The cube in Figure 3 shows three factors that seem most important. The horizontal axis shows the nature of the uncertainty across a spectrum—is it well-characterized or deep? If it is well-characterized, a predict-then-act approach will tend to work well. If not, RDM may prove more effective. The axis going into the page shows the richness or sparseness of the decision options across a spectrum—that is, do decision makers have many alternative options or not? If decision makers have few options—if their choice is to jump or not jump—then they have little option but to take their best estimate and make a predict-then-act decision. But the more that decision makers have a richer set of choices to choose from—for instance, they can pursue an adaptive strategy that adjusts over time depending on how the situation evolves— the more RDM becomes a very attractive approach.

The vertical dimension captures the complexity the decision problem along a spectrum. A less complex problem is one where experts can reliably think through all the steps that connect actions to consequences. A complex problem is one where even experts need a model to follow the causal chains. Research shows that even experts lose track in novel circumstances when such chains become longer than three or four steps. For simple problems, decision makers can often use a traditional scenario planning. But the more the problem becomes complex, the more they should turn to RDM.

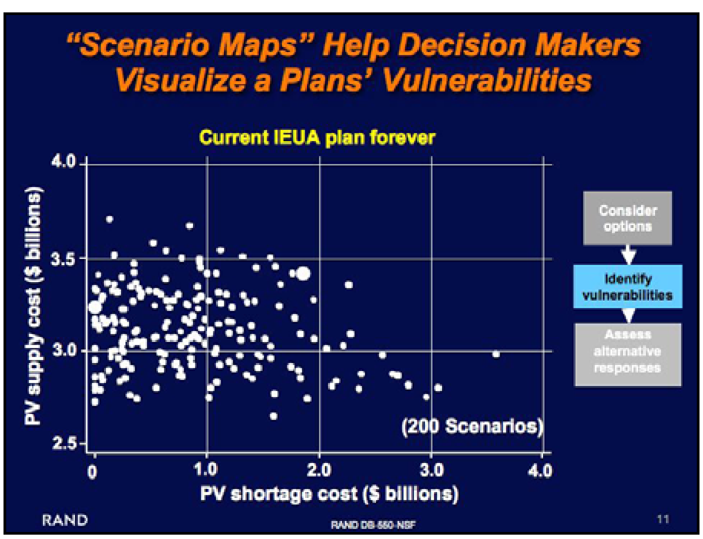


Figure 11. IEUA scenario map with multiple scenarios.

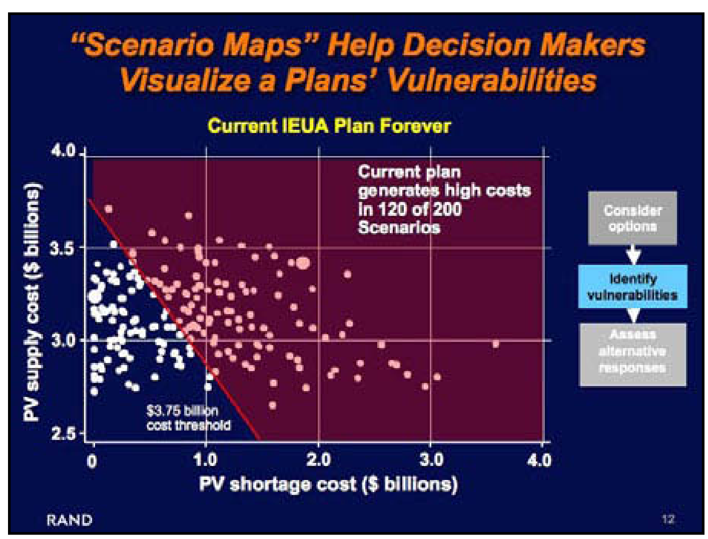


Figure 12. IEUA scenario map indicating scenarios that exceed cost threshold of $3.75 billion.

Application to Long-Term Water Management

I now turn to an example of how RDM works in practice.

Our RAND group is actively engaged in helping a number of natural resource management agencies incorporate climate change into their long-range plans. Climate change represents one of several deep uncertainties with which these agencies must contend.

One of the first such RDM analyses we conducted was in partnership with Southern California's Inland Empire Utilities Agency, or IEUA (Groves et al., 2007, 2008; Groves, Davis, Wilkinson, and Lempert, 2008). IEUA serves about 800,000 people in the Santa Ana, California, watershed. Like all water agencies in California, IEUA is legally required to prepare a long-range plan that demonstrates its ability to reliably provide water to its customers. At the time of the study, IEUA obtained over 80 percent of its water from groundwater and imports, as shown in Figure 4. IEUA prepared its last plan in 2005, which called for increasing replenishment, treatment, and uses of its groundwater resources and substantially increasing the use of recycled waste-water.

However, IEUA had not considered the potential impacts of climate change, so in 2007 we worked with them to conduct an RDM analysis to determine what, if any, changes they might need to make in their plans (Figure 5).

As a first step, we gathered information about the range of future climate in the IEUA region. Working with Claudia Tebaldi at the National Center for Atmospheric Research (NCAR), we used state-of-the-art probabilistic forecasts produced from an ensemble of 21 climate models to estimate the potential change in temperature and precipitation by 2030 (Groves, Tebaldi, and Yates, 2008). These results, shown in Figure 5, suggest that it is virtually certain to get warmer in IEUA's region and likely to get significantly drier. But there is a small chance the climate may actually get wetter. Even this level of uncertainty seems vexing for water managers. But even these wide distributions must be regarded as imprecise. The climate models that produced them do not characterize the historic variability in the region very well, and these projections take the system into novel regions where there is little data against which to validate the models. As we will see, the RDM analysis is designed to handle such imprecision in these estimates.

As a next step, we converted the regional climate forecasts into a set of regional weather sequences suitable for us in our water planning models (Groves, Tebaldi, and Yates, 2008), as shown in Figure 6 . David Yates of NCAR, applied his KNN method (Yates et al. 2003) to generate weather sequences for us that reproduced the trends from the climate models but with the same monthly and annual correlations as seen in the weather records for IEUA's region. The Figure shows several such sequences, one for wetter future conditions, one for drier future conditions, and one for future conditions similar to today's.

One advantage of RDM is that it facilitates the use of a wide range of different types of information in the analysis. For instance, we have recently been developing future weather sequences for the IEUA region that are consistent with significant drought events in the paleoclimate record, as suggested by Figure 7 (Tingstad, Groves, and Lempert in preparation). Such cases are useful to consider because they provide one estimate of the future climate variability the agency might face

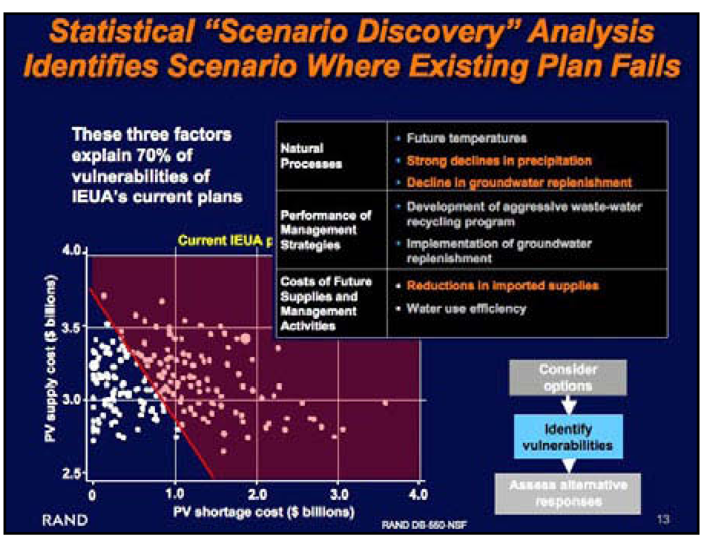


Figure 13. Results of scenario discovery analysis showing vulnerabilities of IEUA's current plan.

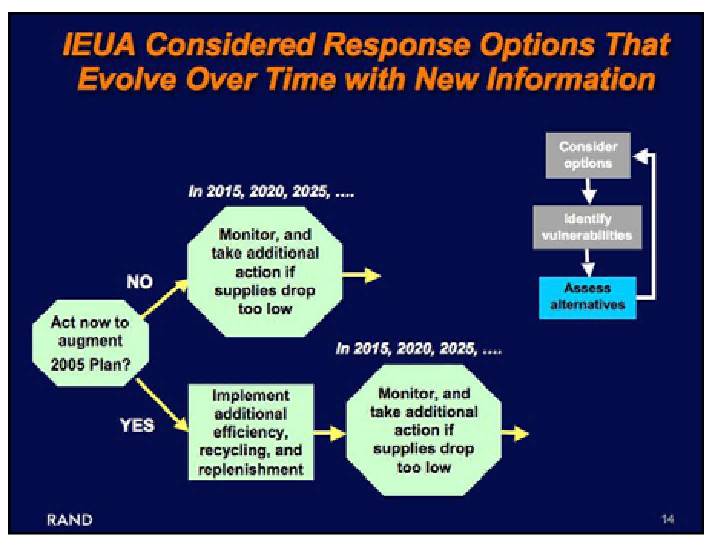


Figure 14. Adaptive "Act Now vs. Act-Later" strategies considered to respond to vulnerabilities of current plan.

that is beyond the capability of current climate models to represent. However, it has proved difficult to include paleoclimate information alongside protections from climate models in water management analyses using most decision analytic methods because there is no way to estimate the probability of the paloeclimate-derived scenarios. RDM's vulnerability-and-response-option-analysis framework allows analysts to sidestep this problem. Our current work (which I will not discuss further in this paper) suggests that any IEUA plan robust against a wide range of climate scenarios derived from climate models is also robust against future scenarios derived from paleoclimate analogues.

I now turn to how we used these climate forecasts, as well as uncertain information about other future trends, to assess the robustness of IEUA's current plan. Working with IEUA staff, our team built a simulation model that allowed us to evaluate the performance of alternative IEUA plans contingent on assumptions about future climate change and other uncertainties.

We first used this simulation as shown in the above figure to conduct a traditional scenario analysis, examining a small number of scenarios that seemed particularly germane to IEUA. We first focused on scenarios that explore different assumptions about future climate in the region. Scenario A shows a benign climate, with a small temperature increase and a small decrease in precipitation. In this scenario, IEUA's current plan generates surpluses out through the planning period. Scenario B shows an adverse climate, with large temperature increases and big drops in precipitation. In this scenario, IEUA's current plan works less well, beginning to suffer shortages by the early 2020s.

But climate change is not the only uncertainty IEUA faces. As shown in Table 1 below, the agency also faces uncertainties in its ability to implement its plan, the cost of future imports, and the level of future water use efficiency. Some of these uncertainties are at least as significant as the future climate ones. For instance, many agencies have had challenges implementing waste-water recycling programs. In addition, trends outside the agency may have an important impact on the success of IEUA's plans. During this analysis, IEUA suffered at least one game-changing event—the court decision on protecting the delta smelt in the San Francisco Bay Delta. Here, we considered a wide range of uncertainties in the cost of imported water and made a wide range of assumptions about how aggressively IEUA's customers would conserve water in the future.

The information available on some of these other uncertain factors is as least as imprecise as the information about the future climate. For instance, we conducted an expert elicitation with IEUA staff and representative of local business and environmental groups to estimate the likelihood that the agency could meet its plan's aggressive goals for waste-water recycling and groundwater replenishment. The results, as shown in Figure 9, suggest that members of the IEUA community harbor some doubt that the 2005 plan could meet its goals.

We can now begin the RDM vulnerability and response option analysis of IEUA's 2005 plan.

RDM often creates scenario maps. The map shown in Figure 10 below charts the performance of IEUA's current plan. The vertical axis records the agency's cost for supplying water. The horizontal axis records the costs of any shortages. Results for two scenarios, one benign and one adverse, are plotted on the map. These scenario maps are analogous to the ones Casey Brown showed in his presentation.

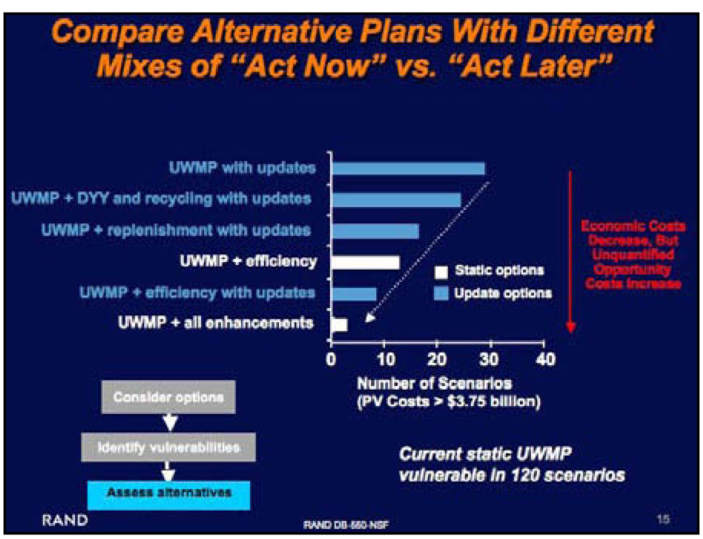


Figure 15. Comparison of alternative response options to vulnerabilities of IEUA's current plan.

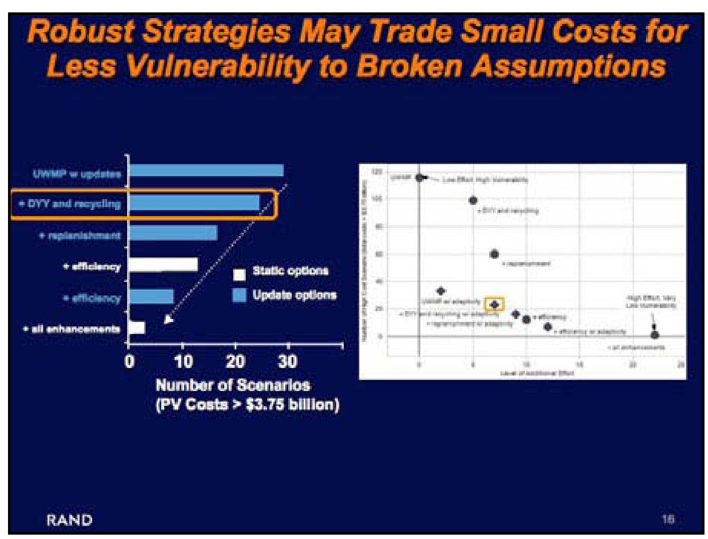


Figure 16. Tradeoff curve (on the right) comparing alternative response options to vulnerabilities of IEUA's current plan.

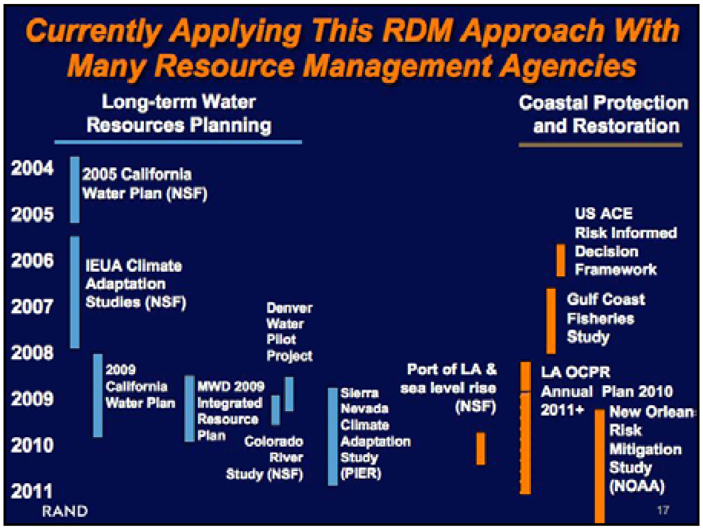


Figure 17. Other Robust Decision Making applications.

The map shows the performance of IEUA's current plan in those two scenarios. Scenario A has a benign future climate (and, thus, leads to no shortages), and the plan has a present value supply cost of $3.3 billion. Scenario B has an adverse climate, which leads supply costs of $3.4 billion and shortage costs of $1.9 billion.

Our RDM analysis now runs the simulation model many times to evaluate the performance of IEUA's current plan over a wide range of scenarios. Each of the two hundred scenarios shown on the map in Figure 11 above represents one run of the model with one combination of the assumptions shown on the previous slide. We chose the set of combinations to provide the best statistical sample of the model's performance over the range of these uncertainties.

The two large dots show the two scenarios, A and B, we considered previously.

Clearly, the cost of IEUA's plan could vary over a wide range, depending on what the future brings.

How can IEUA make sense of all these scenarios? RDM helps them do so in two steps.

As shown in Figure 12 below, we first divide the scenarios into two types—those where IEUA's plan performs well and those where it performs poorly. IEUA set the dividing line between these two cases at a value of $3.75 billion, 20 percent more than their best estimate forecast; this yields the diagonal dividing line shown in the figure. If the plan costs less (about 80 scenarios in the unshaded area), the plan succeeds. If it costs more (about 120 scenarios in the shaded area), the plan performs poorly.

We next ask—what are the key characteristics of these poorly performing cases shown in the shaded area of the map (Figure 13)?

A statistical cluster analysis, which we call "scenario discovery" (Groves and Lempert, 2007; Bryant and Lempert, 2010), reveals an important commonality among the 120 scenarios in the shaded high-cost region. Of all the uncertain factors considered, three emerge as most important. If IEUA suffers a significant decrease in precipitation, a 4 percent or larger decrease in its ability to capture precipitation as groundwater, and greater than expected climate impacts on its imported supplies. However, if any of these three conditions does not occur, IEUA's current plan is likely to perform well.

These three conditions explain about 46 percent of the cases where IEUA's current plan does not meet its performance goals. Thus, the conditions represent the key vulnerability of IEUA's plan.

It is important to note that climate change alone is not likely to cause IEUA's plan to fail. Rather, climate change can make IEUA's plan "brittle." If everything else works well, our analysis suggests IEUA can weather the next few decades of climate change. But if the climate turns adverse and something else goes wrong, the agency could suffer. That is, it is climate change combined with other adverse events that really causes the agency difficulties. The RDM approach has thus provided the agency with what is often called a "multi-stressor" vulnerability analysis. RDM next helps identify and evaluate alternative responses to these vulnerabilities.

When it came to responses, IEUA officials were particularly interested in the question—what do we need to do now, and what can we defer until later? Although this is an obvious question, all of IEUA's previous plans were static. That is, every long-range plan assumed it would continue for decades, even though it was updated every five years. As shown in the Figure 14, RDM allowed IEUA to consider adaptive plans, ones that would take actions now, monitor conditions, and then respond accordingly (Lempert and Groves, 2010).

Working with IEUA, we identified six potential modifications to their current plan, labeled in Figure 15 below as UWMP, for Urban Water Management Plan. Each alternative consists of actions IEUA could take today. Some plans (shown in blue) are adaptive, monitoring trends in the supply and demand for water and then responding in a prescribed way if these trends deviate too far from those forecast. This chart compares these plans, measuring their performance by the number of scenarios in which they are vulnerable—that is, where the present value costs are greater than $3.75 billion.

Natural processes	• Future temperature • Future precipitation • Changes in ground water processes
Plan Implementation	• Success of aggressive waste-water recycling program • Success of ground water implementation program
Costs of future imports and water use efficiency	• Imported supplies • Water use efficiency

Table 1: Uncertain Factors Considered in This Analysis

Recall that IEUA's current plan is vulnerable in 120 scenarios. Just making the plan adaptive (labeled "UWMP with updates") reduces the number of scenarios in which IEUA's plan is vulnerable from 120 to about 30. Taking more near-term actions reduces vulnerabilities even more.

Nonetheless, there are some difficult-to-quantify costs involved with moving down the list of options shown in Figure 15. Options further down the chart may require more staff time, or more persuasion of the community, to implement. The agency chose to modify its 2005 plan by augmenting its recycling and dry-year yield programs in the near-term and committing itself to monitoring and taking additional actions if necessary in the future. For IEUA management, this plan represents a reasonable balance between the effort needed to implement the plan and the vulnerabilities reduced. As shown by the RDM analysis, this new adaptive plan is considerably more robust against a wide range of climate and other uncertainties than is IEUA's current plan.

IEUA officials used the chart shown in Figure 15 and the arguments behind it to help build support for its new plan throughout its community.

Although IEUA officials found Figure 15 very useful for their purposes, we have also generated more formal trade-off curves for research, as shown on the right-hand side of Figure 16 (Lempert and Groves, 2010). The vertical axis shows the number of scenarios where that strategy remains vulnerable. The horizontal axis provides our judgment about the level of effort IEUA staff would need to expend to implement each of these strategies.

On the upper left is the current plan. It is vulnerable in many cases but requires the least effort to implement. On the lower right is the most difficult to implement strategy but the one that performs well in all the scenarios we considered. The strategies marked with diamonds are adaptive. The ones in circles are not. Some options are clearly dominated by the others. The remaining options lie along an "efficient frontier." Not unreasonably, the IEUA managers chose a strategy near the knee of the curve. One could make a good argument that such a strategy is robust.

In other work, we have also used trade-off curves, such as the one shown in Figure 16, to incorporate imprecise probabilistic information into the analysis using the concept of probability thresholds (Lempert and Collins, 2007; Dixon et al., 2007). That is, we ask, what likelihood would the vulnerable cases have to have to justify choosing a decision option toward the lower right-hand side of the trade-off curve. We then compare this threshold to the probabilistic estimates, such as those shown in Figures 5 and 9 above, to give policymakers a sense of whether the threshold is far above, far below, or in the vicinity of the best available estimates. If the best estimate is far above the threshold, then adopting the new policy might be justified. If it is far below, then the new policy might be less justified. If the best estimate is in the vicinity of the threshold, the choice is unclear, and policymakers might wish to design additional decision options in an attempt to find one that proves more robust.

Evaluating the Impacts

We have heard important discussions about validating models at this workshop. I want to talk about another type of evaluation—measuring how effective the approach I have outlined can be at improving water managers' understanding of the challenges they face and how best to respond to them.

We ran a series of four workshops with IEUA where we presented modeling results to participants, including the agency's management and technical staff, local elected leaders, and representatives from the local business and environmental communities. The workshops were organized around "bake-offs" between different approaches for presenting the same data and modeling results. In particular, we compared traditional scenario approaches, using scenarios such as those in Figure 8, a probabilistic approach, and the RDM approach. We conducted surveys at various times during the workshops

We learned a great deal from these workshops (Groves et al., 2007, 2008). Participants reported trade-offs between the simplicity and usefulness of the alternative approaches. In particular, they found the traditional scenario methods easiest to understand and communicate to others, but they found the RDM approach the most useful for informing their planning process. We used these initial results to try to improve the clarity of the RDM approach. For instance, participants preferred the scenario maps with scatter plots presented in Figures 10-13 to other types of graphical displays, such as histograms.

The workshops changed participants' views about the challenges facing IEUA. After the workshops, 35 percent reported that they believed the consequences of adverse climate change in IEUA's region appeared "more serious" than they had previously, 40 percent thought the likelihood of adverse climate change outcomes for the IEUA was "greater" than before, and 75 percent though the ability of IEUA planner to plan for and manage effects was "greater" than before.

Finally, our surveys detected what I think is a very interesting pattern. Our participants included a mix of people initially concerned with climate change and those skeptical of it. During the course of the workshops, participants' willingness to believe that IEUA had a climate-change problem only emerged once they became more confident that IEUA could respond to that problem.

Participants emerged from this exercise feeling that climate change was more immediate and potentially more abrupt than they had thought and that there was more that they might be able to do about it than they had originally thought. Although these are small samples, they do give some indication and certainly some sense that it is the ability to do something about climate change that precedes the belief that it is a problem. This pattern certainly makes sense. People are not particularly interested in hearing that they have problems that they cannot solve; as a result, they tend to reduce the cognitive dissonance by ignoring such warnings. But once convinced that they can actually solve a problem, they are much more receptive to the information about it.

Summary

RDM appears to be an effective approach for helping water managers plan under conditions of deep uncertainty. This workshop addresses one key example of such conditions—those where natural resource agencies have to relax previous assumptions about a stationary climate and replace them with imprecise and potentially irreducibly uncertain forecasts of future climate. As shown in Figure 17 below, we are now using RDM to support a wide variety of agencies, including a small project for our next speaker—Marc Waage from Denver Water. In addition to our work with water management, we are also using RDM to help agencies involved with coastal protection and restoration. We have a series of projects in Louisiana and are helping the Port of Los Angeles develop a response to sea-level rise. These projects are similar to that shown here for IEUA, but they also incorporate RDM's approach for managing responses to the potentially very serious, low-probability "fat tails" of the climate impacts distributions (Lempert and Collins, 2007).

In summary, RDM has three key features:

- Characterizes uncertainty with multiple views of the future, either multiple states of the world as in the IEUA example or sets of multiple probability distributions.
- Employs a robustness criterion to compare alternative strategies as opposed to optimality criteria.
- Conducts an iterative vulnerability and response option analysis to help managers identify better decision options.

Fundamentally, RDM is not an approach designed to make better predictions of the future. Rather, it aims to use the available information to help decision makers develop options—in particular, ones they may not have considered previously—that are more robust to the deep uncertainties they face. In brief, RDM works by helping decision makers reframe the question from "What will the future bring?" to "What steps can we take today to most assuredly shape the future to our liking?"

Acknowledgments

The author acknowledges the generous support of the National Science Foundation (Grant SES-0345925).

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Also see: www.rand.org/ise/projects/improvingdecisions/

Biography

Robert Lempert is a senior scientist at RAND and Director of RAND's Frederick S. Pardee Center for Longer Range Global Policy and the Future Human Condition. A pioneer in developing new methods to harness information technology in support of decisions under deep uncertainty, Dr. Lempert's research focuses on developing and deploying new approaches to supporting climate-related mitigation and adaptation decisions in a wide range of areas. His research group at RAND is currently helping several natural resource agencies incorporate climate change into their long-range plans. Dr. Lempert serves on the National Academy of Sciences America's Climate Choices Study Panel on Informing Climate Decisions, is a lead author for the Intergovernmental Panel on Climate Change (IPCC) special report on managing extreme events and disasters, and was an author of the U.S. Climate Change Science Program report on Best Practice Approaches for Characterizing, Communicating, and Incorporating Scientific Uncertainty in Decisionmaking. Dr. Lempert is a Fellow of the American Physical Society, a member of the Council on Foreign Relations, and a member of the National Academy of Sciences' Climate Research Committee. A Professor of Policy Analysis in the Pardee RAND Graduate School, Dr. Lempert is an author of the book Shaping the Next One Hundred Years: New Methods for Quantitative, Longer-Term Policy Analysis. He earned his B.A.S. in physics and political science from Stanford University and his Ph.D. in applied physics from Harvard University.

Nonstationarity Water Planning Methods

Marc Waage, Denver Water

Abstract

Climate change is challenging the way water utilities plan for the future. Observed warming and climate model projections now call into question the stability of future water quantity and quality. As water utilities grapple with preparing for the large range of possible changes in climate and the resulting impacts on their water systems, many utilities are searching for planning techniques to help them consider multiple possible conditions to better prepare for a different, more uncertain, future. Many utilities need these techniques because they cannot afford to delay significant decisions while waiting for scientific improvements to narrow the range of potential climate change impacts. Several promising methods are being tested in water utility planning and are presented here for other water utilities to consider. The methods include traditional scenario planning, classic decision making, robust decision making, real options, and portfolio planning. Unfortunately for utilities vulnerable to climate change impacts, there is no one-size-fits-all planning solution. Every planning process must be tailored to the needs and capabilities of the individual utility.

This paper is based on a presentation given by Marc Waage (Manager of Water Resources Planning, Denver Water) at the Nonstationarity, Hydrologic Frequency Analysis, and Water Resources Management workshop held in Boulder, Colorado, on January 27th, 2010. The presentation illustrated a number of key messages developed by the Water Utility Climate Alliance in a white paper released January, 2010 .

Introduction

Water industry discussions about climate change are rapidly evolving. They are moving beyond the debate of whether or not the climate can or will change and why, to what changing conditions could a utility eventually be expected to deal with and how to best plan for uncertain future climatic and hydrologic conditions in addition to all the other uncertainties water utilities now must consider. Integrating the wide range of climate change projections into water planning is one of the most challenging steps utilities face in the climate change adaptation process. Planning is one of four basic steps in the climate change adaptation process for water utilities (Means, et al., 2010):

1. Understand - understand climate science and climate model projections,
2. Assess - assess water system vulnerabilities to potential climate changes,
3. Plan - incorporate climate change into water utility planning, and
4. Implement - implement adaptation strategies.

In the first step, many utilities develop an understanding of climate science, climate system modeling, downscaling techniques, current climate projections, and regional implications. Using information gained in the understanding process, water utilities next assess their system's vulnerabilities to climate change. They perform analyses to identify potential impacts to the natural hydrologic systems supplying their water, and use the results to assess their water system's vulnerabilities. The next step is to incorporate the findings from these vulnerability assessments into their planning process in order to develop adaptation strategies. In the final step, decisions are made and strategies implemented that help water utilities adapt to potential impacts from climate change and reduce system vulnerability. Few utilities have reached the planning and implementation steps (Means, et al., 2010). Although the process moves from understanding, through analysis and planning, to action, not all utilities will follow the same steps.

There presently are a large range of climate projections for many regions, and many agencies are not comfortable selecting one projection over another. Vulnerability assessments, consequently, tend to consider a variety of different projections. While more sophisticated climate models and methods are being developed, it could be many years before the range of projections, and the uncertainties about the projections, are substantially narrowed (Barsugli et al., 2009). In the meantime, water utilities will have major decisions to make with financial, social, and environmental impacts that can be substantially affected by climate change. To help prepare for this climatic uncertainty, many water utilities will need to develop planning methods that consider multiple possible future conditions.

Planning for Multiple Futures

Water supply planners tend to rely on the past hydrologic records to represent future water conditions. Many parts of Colorado, for example, have more than 100 years of streamflow and weather records that water supply planners use to understand and prepare for the state's highly variable hydrology (Waage and Kaatz, 2010). Past hydrology is assumed to be a satisfactory predictor of future conditions. Climate change fundamentally threatens this assumption. With climate change, hydrologic statistics and variability are expected to continuously shift (Milly et al., 2008), and unfortunately for many areas, the projected ranges of shifts are extremely large. Despite this uncertainty, past hydrologic records are still the best guides to future water supply conditions. Many water suppliers use sophisticated techniques for analyzing and reconstructing historic hydrology back hundreds of years beyond the observed records (Smith, et al., 2010). This prepares water providers for a much greater range of hydrologic variability, but this only plans for one basic outcome – the repeat of past hydrologic patterns.

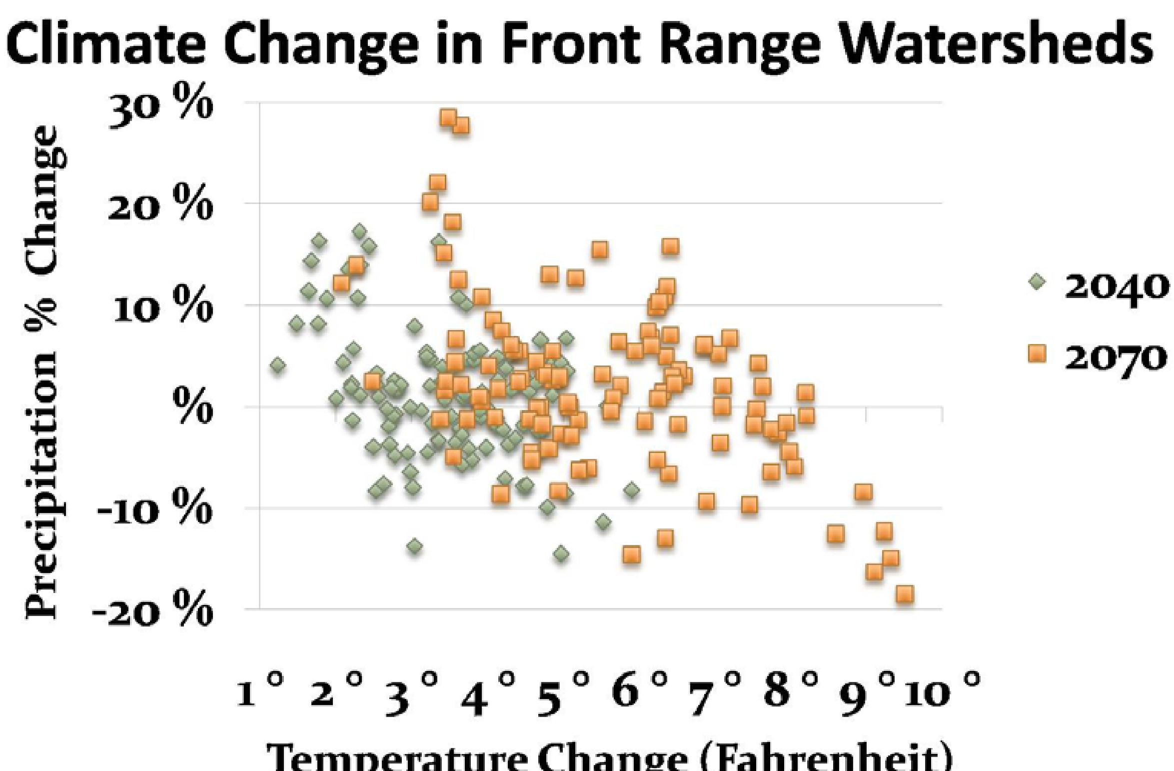

Figure 1. Presented changes are comparisons of 30 year averages around 2040 and 2070 to 1950-1999 averages based on 112 statistically downscaled projections from 16 climate models used to simulate low, medium and high emission paths. Information courtesy of the Joint Front Range Climate Change Vulnerability Study.

Denver Water's Experience

Figure 1 shows projected temperature and weather changes for the upper portions of the South Platte, Colorado and Arkansas rivers (Kaatz, 2009). Most of Colorado's municipal water supply, including Denver's, comes from this area. Weather records show this area is warming, and climate models project more warming (Ray et al., 2008). Climate models, though, do not agree on how much and how quickly it will warm. And the stakes are high.

A simple assessment of Denver's watersheds showed a warming of 5°F would cause a 14% decline in water supply (19% decline in streamflow), which is nearly the amount of water used by 100,000 households in Denver (DW, 2005). But what will happen with precipitation is the real wild card. As shown in Figure 1, about half of the climate models project declining precipitation, while the others project an increase. Planning for warming along with both increase and decreases in precipitation is a difficult feat for water utilities.

Temperature change is only one new variable of concern. Over the last decade Denver's watersheds underwent fundamental changes. In 2002, a severe drought caused streamflow in the South Platte River to dip to the lowest levels on record. Also, the largest forest fire on state record, the 2002 Hayman Fire, destroyed thousands of acres of forest in an area already damaged by the 1996 Buffalo Creek Fire. Those fires caused sediment problems in the South Platte watershed, and managing those problems now costs Denver Water tens of millions of dollars. (Waage and Kaatz, 2010) In the West Slope watersheds, pine beetles have killed nearly all of the lodgepole pine trees, which increase the risk of wildfires and quality degradation. Along with continuing changes to the climate and watersheds, many water suppliers in Colorado now struggle with how to prepare for shifting social, political, regulatory, environmental and economic conditions.

With so many planning variables combined with preparing for both past hydrologic variability and uncertain shifting future patterns, water providers need multiple outcome techniques to prepare for a much greater range of possible future conditions.

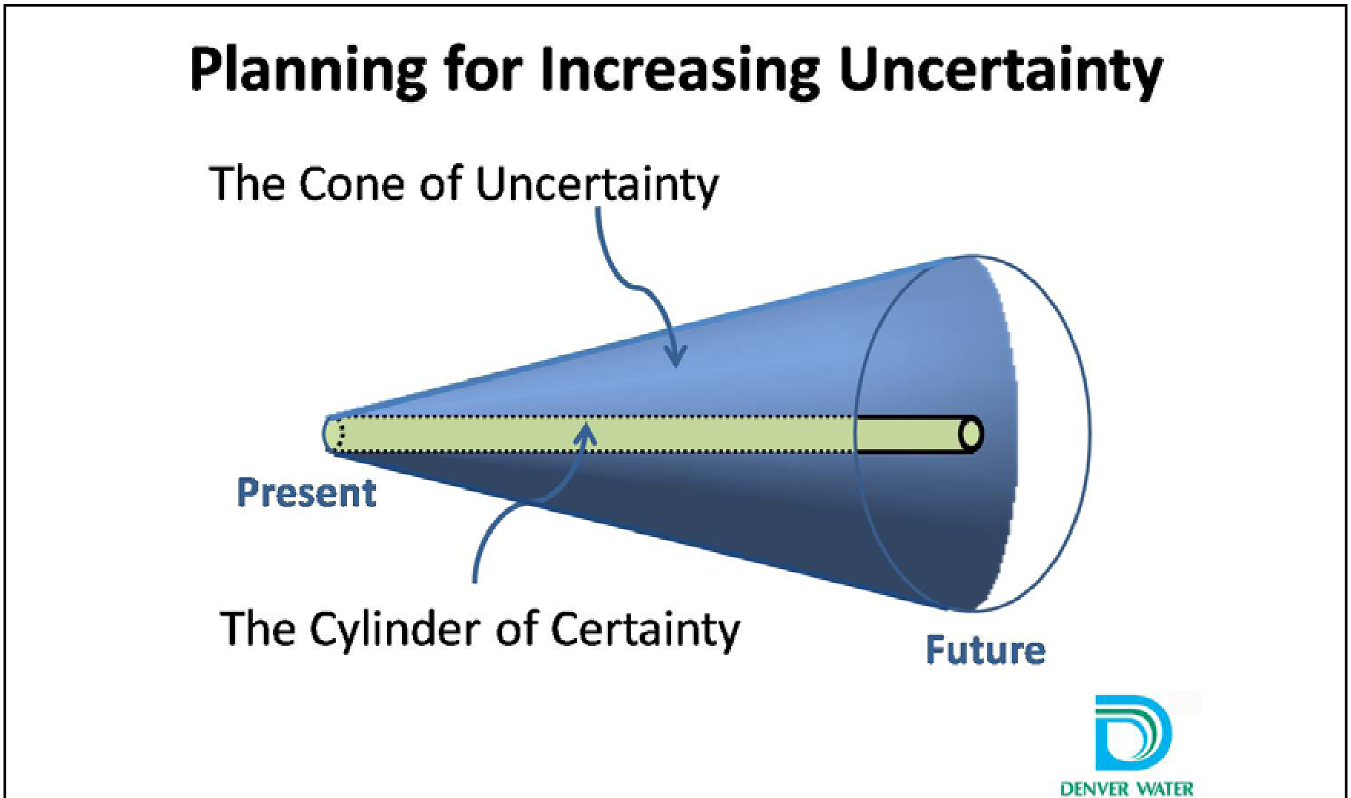

Figure 2. The Cylinder of Certainty and the Cone of Uncertainty. A depiction of increasing uncertainty with time.

Five Multiple Outcome Planning Method Options

The Water Utility Climate Alliance, in an effort lead by Denver Water, identified and evaluated municipal water planning methods specifically designed to prepare utilities for many possible future conditions. In January (2010), the Water Utility Climate Alliance published a guide for water utilities titled, "Decision Support Planning Methods: Incorporating Climate Change Uncertainties into Water Planning." The report found that while some water utilities have been using multi-outcome methods for many years, most are not. The following five methods were presented based on their use (or potential for use) in municipal water planning (Means, et al., 2010; Morgan et al., 2009).

Traditional scenario planning seeks to identify near-term actions that prepare a utility for several different, plausible, and often provocative future scenarios (Schwartz, 1991). The goal of this approach is to develop a range of future conditions (scenarios) that go beyond extrapolation of current trends and represent surprising but plausible conditions. Typically, scenarios are treated as equally likely to occur. Implications and future needs for each scenario are identified and adaptation strategies are developed. Ideal adaptation strategies have near-term actions that are common to all or most scenarios. These are sometime called No Regrets or Low Regrets strategies. Signposts can be established to monitor the development of the scenarios and determine when adaptation measures are no longer common to all or most scenarios. A benefit of traditional scenario planning is that those involved in the planning process do not need to agree on a single future when developing the plan.

Classic decision analysis supports water utility planners by systematically cataloging information and mathematically evaluating and ranking decision alternatives against multiple, potentially conflicting, decision objectives. The process is illustrated through decision trees or influence diagrams. Uncertainty is handled through the use of probabilities. Classic decision analysis is used to find a preferred plan with the best value (Clemen and Reilly, 2004)

Classic decision analysis techniques have been used in some water planning applications for many years. When considering climate change uncertainty, though, assigning probabilities to future conditions can be difficult and hard to defend. Currently there is no scientific consensus on the validity of assigning probabilities to climate model projections (Stainforth

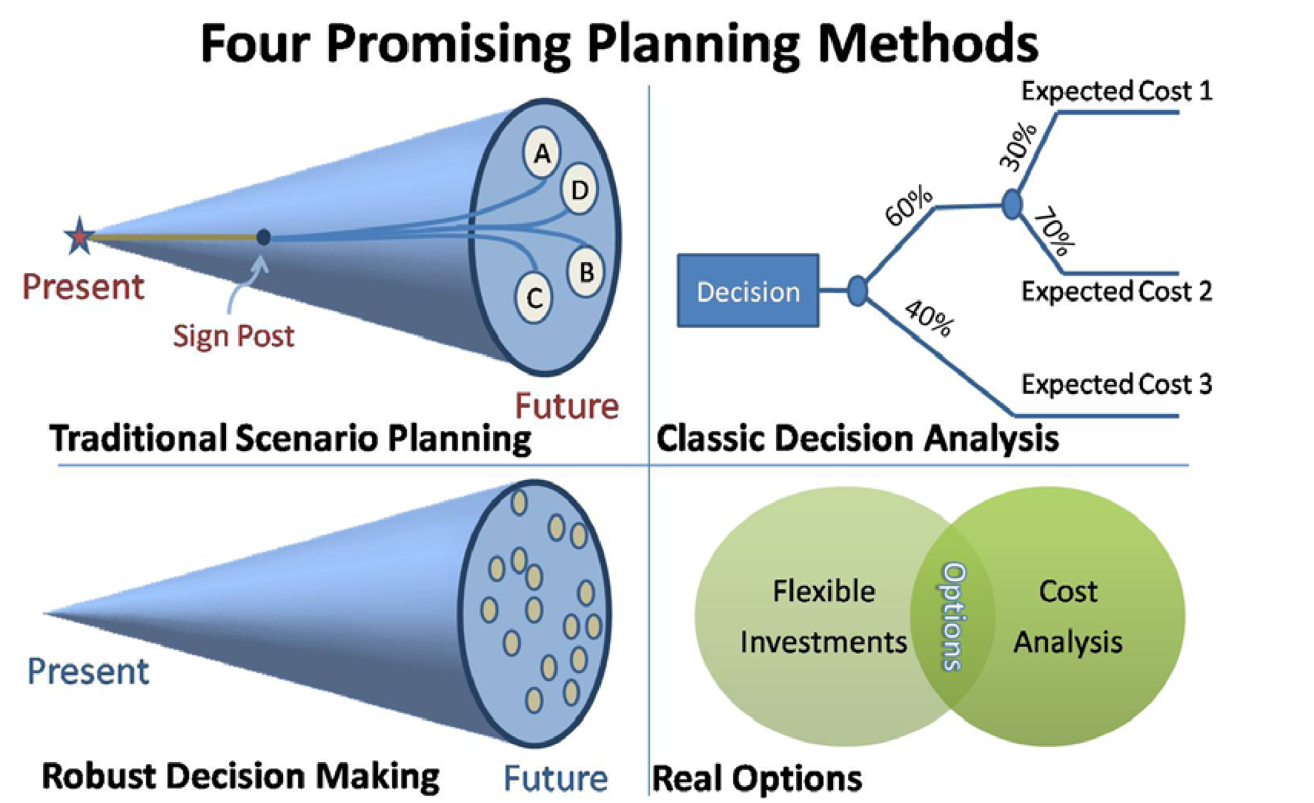

Figure 3. Traditional scenario planning, classic decision analysis, robust decision making, and real options method illustrations.

et al., 2007a and 2007b). Water utilities deciding whether to use classic decision analysis for climate change planning must carefully consider their willingness, and ability, to assign probabilities to climate model projections.

Robust decision making uses complex modeling processes and combines features of both decision analysis and scenario planning to develop adaptation hedging strategies for a large number of future conditions (Groves and Lempert, 2007). The approach provides a systematic way of developing a water management strategy to best adapt to a wide range of plausible future conditions. Robust decision making is particularly useful when agencies want to examine uncertainties that cannot easily be assigned probabilities. Also, it does not require agreement by decision makers, experts, or stakeholders on the likelihood of different future conditions occurring. Sophisticated techniques are used in conjunction with existing water management models to evaluate candidate strategies and then to identify major vulnerabilities within these strategies. Analysts, stakeholders, and decision makers study these vulnerabilities to develop hedging options and to design alternative strategies. Successive iterations through these steps reveal increasingly robust strategies. The method is most useful when there are many decision alternatives and a detailed analysis of every possible alternative is not possible.

Real options is a method to help water managers identify water supply strategies that adjust over time and balance risks. The method determines sets of strategies that maximize value by using traditional discounted cash flow approaches. Flexible investment strategies are sought that can be risk-adjusted with time and deferred into the future. Uncertainties in real options are handled through the use of probabilities. Results are flexible in that they may incorporate delaying and phasing of facility projects (WSAA, 2008).

Portfolio planning is used in the financial world to select a portfolio containing a mix of assets or strategies that minimize financial exposure due to future market scenarios. Uncertainty is handled through the use of probabilities and Monte Carlo simulations, and minimized through hedging. The approach has been included as an example of how other sectors handle uncertainty. This method currently is not used in water supply planning, but is intended to exemplify the potential use of other uncertainty management methods by the water industry (Crowe and Parker, 2008).

Discussion

Figure 2 demonstrates the difference between planning for a repeat of past hydrology and planning for a growing range of possible future conditions. The Cylinder of Certainty represents projecting the future from the past, particularly in terms of repeating hydrology. The cylinder contains variability but that variability is limited to a snapshot of what has happened in the past. The Cone of Uncertainty represents uncertainties that grow over time, such as climate, social, environmental, regulatory, political and economic changes (Waage, 2009).

Traditional scenario planning tries to identify several points on the end of the cone and develops near-term strategies to simultaneously prepare utilities for those future conditions. Using complex modeling, robust decision making tries to identify 100 or more points on the end of the cone and develops hedging strategies to prepare utilities for those conditions. Both methods seek No (or Low) Regret strategies, that provide the utility with flexibility to react to a range of future conditions. Classic decision analysis, real options and portfolio planning estimate the probabilities of reaching various points on the cone and determine strategies that minimize expected future costs. Figure 3 depicts traditional scenario planning, classic decision analysis, robust decision making, and real options.

Conclusions

Every planning process must be tailored to the needs and capabilities of the utility, and, unfortunately, there is not a one-size-fits-all approach. For utilities not interested in methods requiring sophisticated computing or modeling, scenario planning is fairly intuitive and can be accomplished with minimal external resources. On the other hand, utilities looking for, and confident in, a probabilistic assessment may look to classic decision analysis. Utilities that want to invest more resources and rigor into climate change adaptation strategy development may consider more advanced computational methods or hybrid methods such as robust decision making, real options, or portfolio planning.

There are several questions a utility should consider as they explore their climate change planning options.

- How do you want to deal with probability?
- How much time do you want (or have) to invest in assessing uncertainty?
- How important are quantitative results to your audience?

- What internal modeling skills do you have?
- How much money do you want to invest?
- What is your willingness to hire external help?
- To what level do you want (or have) to include stakeholders in the analysis?
- How technically sophisticated are your stakeholders?
- How will you use the results?

Considering these questions will help the utility select a method(s) to best suit their particular planning needs.

As water utilities plan for a greater range of future conditions, they are no longer developing plans around a single future. They are seeking robust strategies that may not be optimum for any one projection of the future, but in the long run, will provide water utilities with better options and more flexibility to adapt to changing conditions.

Next Steps

Only a handful of water utilities have reported using multi-outcome planning methods. Denver Water and the Water Utility Climate Alliance are interested in promoting more research, evaluation and development of multi-outcome water planning methods, as well as encouraging more use of these methods by the water industry and sharing utilities' experiences through case studies. We encourage you to read our guide, found at www.wucaonline.org, and give us your feedback.

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Biography

Marc Waage is leading the development of Denver Water's new long range water plan. Prior to this assignment, Marc managed the operation of Denver Water's extensive water supply system for twenty years. Denver Water is the largest and oldest municipal water provider in Colorado. Marc is also co-leading the development of a climate change decision support analysis for the Water Utility Climate Alliance. Early in his career, Marc worked for the Bureau of Reclamation and the Bureau of Indian Affairs on irrigation projects in Colorado and Montana. Marc has a Bachelor's degree (with high distinction) and a Master's degree in Civil Engineering from Colorado State University and is a professional engineer. One of Marc's favorite activities is recreating in Denver's high mountain watersheds.

Approaches to Nonstationarity

Planning Hydrology Based on Blends of Instrumental Records, Paleoclimate, and Projected Climate Information

James Prairie, U.S. Bureau of Reclamation

Abstract

Planning studies are critical during evaluation of changes to water supply, demands, or reservoir operating policies. These studies allow water management agencies, such as the Bureau of Reclamation, to evaluate the impacts of proposed changes in a river basin system under their management and convey their findings to critical stakeholders and the general public. Planning studies typically structure an assumption of future water supply, demands, and reservoir operations and represent changes to one or a combination of these assumptions versus present conditions.

Future water supply assumption or planning hydrologies are typically developed from information based on observed gauge records. Planning hydrologies based on these data assume that future conditions can be represented by the climate events of the observed past. Recent evidence has shown the observed past may not provide an adequate proxy of future climate. It is becoming increasing difficult to depend on planning hydrologies that are solely based on information provided by the recent observed past.

In the Colorado River Basin, until 2007 planning studies only utilized a naturalized flow dataset that extended back to 1906. This record was built from observed records that capture the hydrologic variability observed over the last century. Though the Colorado River Basin has a "long" observed dataset, in the eyes of many practitioners the basin has been recently enduring a drought that is unprecedented in its observed record. The current drought that began in 2000 continues today producing the lowest ten year average flow in the last hundred years.

This unprecedented drought has provided an excellent opportunity for Reclamation to explore alternate methods to develop planning hydrologies that go beyond dependence on the observed past. As a first step Reclamation sought to re-introduce paleo-reconstructed streamflows. These reconstructions provide a window into the distant past, significantly enhancing relevant frequency characteristics in a planning hydrology and incorporating climate information from the past one thousand years rather than just the last one hundred. Such reconstructions have been available in the Colorado River basin since 1976 but have not gained wide acceptance in planning studies.

Though reconstructed streamflows provide rich information and should be incorporated in planning hydrologies, the magnitudes of reconstructed streamflow can have a high degree of uncertainty. When creating a reconstruction a regression model is fit to the observed streamflow with a collection of tree ring observations as the predictors. This fitted model is then used to estimate streamflows in the pre-observational period using the tree ring observations. The reconstructed streamflows can be sensitive to the choice of model as demonstrated by Hidalgo et al. (2000). This apparent weakness of the paleo reconstructed flow data has rendered their use in a water resources planning context questionable, despite the availability of paleo reconstructed data for many decades. Despite these apparent weaknesses, few argue about the duration and frequency of dry and wet (i.e., the hydrologic state) periods from the reconstructions.

Recognizing the limitations of relying on only the instrumental record for long-term planning studies, Reclamation devised a framework to combine the long paleo reconstructed streamflow information of lower reliability with the shorter but reliable observational data. The framework blends paleoreconstructed hydrologic state (i.e., wet or dry) with instrumental records magnitudes. With these datasets the framework addresses generating simulations for planning studies with drought and surplus spells that demonstrate the persistence underlying the lengthy paleo reconstructions.

The blend of the instrumental and paleoreconstruction datasets can address the issue on increased hydrologic variability with a longer record but may not be able to capture the potential for future changes in streamflow that are not represented in either the instrumental or paleoreconstructed datasets. To overcome this issue the framework can easily be modified replacing the instrumental record with flows generated from projected climate information. Incorporation of projected climate information incorporates projected changes in the streamflow magnitude distribution characteristics while the blending preserves the persistence characteristic of the longer record paleoreconstruction.

These two variations on the original observation based planning hydrologies allow Reclamation to explore a rich variety of plausible streamflow scenarios that either (1) maintain the distributional and frequency characteristics of the recent observed period, (2) blend the distributional characteristic of the observed period with the frequency characteristics of the paleo reconstructed streamflows, or (3) replace the observed distributional characteristics of the flow magnitudes with those based on projected climate information. In addition to these three scenarios, two more can easily be added by directly using either the (4) paleo reconstructed flows or the (5) flows based on projected climate information without modification.

Reclamation began incorporating the modified planning hydrologies (2) and (4) in a sensitivity analysis of water supply changes for a recently completed Environmental Impact Statement. These analyses allowed Reclamation to begin exploring the potential impacts of only workingwith information from the observed past and evaluating what additional information can be gained from a longer paleo perspective. It is important to recognize that a decision regarding which of the five proposed planning hydrologies is most plausible is difficult, if not impossible. These alternate scenarios should be used to evaluate the sensitivity of potential decisions to changes in the water supply assumption and explore to potential breath of these assumptions.

Introduction

Thank you very much. It's a pleasure to be here today.

I'm going to bring us back to reality, even a little closer than we've been going today, in actually showing you some work that we have completed with our stakeholders in trying to incorporate both climate variability, and then the steps we're taking to start considering a changing climate with our stakeholders.

So I'm going to kind of go back in the past and show you the process we've gone through over the last, about, six years, starting in 2004. From this process, we've developed some methods to blend the instrumental record, the paleo record, and also look at the projected climate information in order to develop planning hydrologies for our long-term studies.

I'm going to give you a quick overview of the Colorado River Basin, kind of describe the current conditions of the basin and describe the interim guidelines of the new process that we went through. Then I'll show how paleoclimate information is brought into that process, and our steps to move beyond the observed record and start to bring this paleo information, and then incorporate climate information, into our actual operations that are occurring at this time.

So for folks who aren't familiar, the Colorado River Basin annually has about 16.5 million acre-feet that are allocated in a basin where the average annual flow is about 16 million acre-feet, so of course, we're over-allocated. Presently, there's 13 to 14.5 million acre-feet of use with a curve that is going up in the future.

The basin is rather notorious for the storage amount -about 60 million acre-feet of storage, about four years of storage. And then the flows are highly variable. That's been to our advantage with this reservoir system. We presently have about 103 years of what we call naturalized flows in the basin that we use for modeling purposes to understand hydrologic variability.

The basin is broken into the upper basin and the lower basin. One of the points of interest is the Lee's Ferry gauge, which is just below Lake Powell.

Here's a graph of the natural flow record. We're going from 1906 to present, to 2010. The last three values, estimated values, are based on forecasted information. We can see the annual data shown in the bar charts, highly variable. You can see the period of some of the critical record, which is the 12-year period in the mid-'50s through the '60s and currently right here, where you see predominantly low flows, but there's periods of high flow.

Then you see the current drought we're in right now that started in 1991 and has brought us to the lowest 10-year flow we've seen on record. We haven't seen a flow lower than this in our observed record.

This is the state of the system at this present time. In 1999, the reservoir system was basically full at 95 percent capacity. The drought started in 2000. We had the lowest unregulated inflow in 2002 of 25 percent into Lake Powell. And we've had fairly below-average flows. There have been about two years above average, 2005, 2008; and this has been enough to hold us at 58 percent capacity between Lake Powell and Mead, so it's buying us time.

The one thing that's interesting is, the system is working exactly as designed. It was designed to prevent shortage in the Lower Basin. To date, there's never been shortage in the Lower Basin, even with this 10-year drought. So, you know, it speaks to the fact that they built this to what they were expecting to happen.

So we are seeing some things that are unprecedented right now, and this has brought us to the current position we're in. The drought ran since 2000. The projected flows for the high flows April through July 2010 is 78 percent of average, so it doesn't look like this year is going to be a year that's going to help us bring those reservoirs back up to a place where people would be much more comfortable.

As I've said, it's not unusual to have some high flows in between these drought periods, but it doesn't mean we're out of the drought. And we have been looking at tree ring reconstructions, because these have been showing more severe droughts than what's occurring right now, and that's something that we thought we really need to start incorporating into our plans, and we're taking steps to begin to do that. I'll show a little bit more about that in the next two slides.

So what's happened through this drought is in 2004, it really prompted us to begin a NEPA process. It's something that the Secretary of Interior came to the basin states and said, something you need to consider, because we didn't have a plan in place of how to deal with shortage should it occur in the lower basin. So there was no set of guidelines saying, this is what you're going to do.

At the time, the Secretary was the water master, so they would have made the decision, but it makes it much easier if there's some plan in place for people to be expecting to occur, so that was really what was put in front of the basin states, and Reclamation was posed as the entity to help bring this about.

And this was begun in 2004, and from that process, we moved through in about a two-year time frame, really, 2005, when it got up and running and developed an EIS study that looked at operating Lake Powell and Mead in a coordinated plan and also developed guidelines for shortages that occur in the Lower Basin.

And that came about to be what's termed the interim guidelines, and we viewed this as a robust solution. It's interim in the fact that these guidelines are only in place until 2026, and a lot of this has to do with the uncertainties of natural flow variability and the fact that we couldn't look much beyond that and put a plan in place that we'd be comfortable with.

But with this interim plan, we were able to specify a full range of operations for Lake Powell and Mead, basically looking all the way from surplus to drought in a coordinated fashion. We were able to develop a mechanism called the intentionally created surplus mechanism.

The idea of this is to start to encourage efficient and flexible use of the water and storage within the Colorado River Basin. It's actually, basically, a type of banking mechanism that allows water to be stored in Lake Powell and used at a later time.

And then also, a strategy for storage was developed for the lower basin with provisions for additional shortage, should that be warranted. Basically, now, there's trigger elevations on the basins, Lake Powell and Mead, that specify certain things are going to occur when you hit these specific elevations. And then there's an elevation that says, if we get this low at Lake Mead, we're agreeing we're going to come back to table and decide what we need to do next, because the storage we have in place isn't enough.

As I said, the interim period is just because we feel that this is going to allow us to gain some operational insight into the changes that we've implemented here and allows us also to start to understand the science of climate change and be able to let it advance so that we can continue to incorporate it in our work and bring it in at a time when we see it's going to be really beneficial to the process which is something we're just beginning to do now.

And then also, the last thing, the basin states agreed to do a consultation before we go into litigation. The Colorado River Basin is pretty notorious as one of the most litigated rivers in the world, so that was a very big accomplishment, to be able to get the states to agree we're going to sit back down before we start to sue each other to try to decide how we're going to deal with these issues as they come up.

So that kind of sets the tone for what's been happening. Out of this work also, there was a climate technical work group that was formed. It was paneled during the interim guidelines, and its goal was to assess the knowledge regarding climate change and the ability to use it in modeling the Colorado River Basin. Also, it was there to help prioritize future research and development to address both climate variability and climate change.

It was paneled by members of a diverse community, community members, university members, and then also from private consulting firms. And the results from this particular study were published in Appendix U of the final environmental impact statement, which is available on the Bureau of Reclamation's website.

Within this group's report, they recommended that hydrologic variability be incorporated into this interim guidelines analysis as a sensitivity analysis, so that was something done in Appendix N in that analysis, and that's something I'll describe a little more in a few slides.

They also specifically recommended that paleo information be brought in to look at hydrologic variability, and that's where the blending came in, when we started to look at ways to assess the methodology we currently used, which are incorporated in some of what was recommended.

And then finally, for the EIS, we only recommended a qualitative analysis of the effects of climate change at the time this was published. That was just because the science wasn't at a point when we were ready to make decisions based on that, but we put a research program in place to start to help advance the science to a place where we can start using it in our particular work, and that's something that I've been leading up to and that we are in the midst of, and we're getting to a point where we're going to be able to start to explore some of the impacts of climate change on some of the decisions we need to make, and I'll describe that very briefly at the end.

So just to come back to the paleo information, one of the key things that came out of that report. You've already seen a slide similar to this. This one is a little more extended. We're looking at the period 762 to present. This is a 10-year running mean, and the observed data is shown in green here. Of course, a very short record.

Across here is the lowest 10-year value from the observed record, and then we have two different recent tree ring constructions. One was done by Woodhouse, et al., and the other was done by Meko, et al. The Woodhouse, et al., goes back about 500 years, while the Meko, et al., goes back about 1200 years.

And what these do initially is, they start to show us that even though we have an observed period in which we've never seen what's currently happening, the paleo has. It's seen more dire situations than this, which is important for us to understand. If we actually go into the long-term Meko record, we actually have one period they're calling medieval drought which looks like it occurs once in a thousand years. It's a scenario that if it occurred would pretty much drain all the reservoirs.

So it's a possibility based on these scenarios. So it's something that at least we can start to convey to our stakeholders, that though it's a small risk, there is a risk that this could come about, and now they need to get in discussions and say what are they going to do and work towards understanding. Is this something we need to design for? Is it not? But at least get the dialogue moving.

And then the other thing is, we can start to understand frequency information much more. The current event we're in, based on the 500-year record and also some of the longer-term records, looks like it's about a 100 year-event. So we're seeing some of the frequency of these longer droughts that we haven't seen before, which is really pretty critical information for our stakeholders to be able to frame for their principles and also to think about.

In Appendix N, the first step was a sensitivity analysis. What we presently used, through almost all our planning studies, is what we called the direct natural flow record. This record takes that short observed period, which you saw in green, and it uses a stochastic method called the indexed sequential method. Basically, it's a sequential block bootstrap. Very simple method. It's something that is really appreciated by our stakeholders. The more complex you get with the method, the more black box you get, the more uncomfortable they are in allowing you to use that in your planning scenarios.

So this has been something that, though paleo information has existed since 1976 in the Colorado River Basin, they weren't ready to take it on until we just went through the event that's going on right now. But using this method, we're able to see some of the variability, but it's only the variability due to the sequencing and the magnitudes of flow that's seen in the observed record. That's the first hydrologic scenario that we're using, and that's the one that really was in the body of the report.

Sensitivity analysis went one step further to say, okay, now we have the paleo information, the longer term one which is the Meko, et al., 2007 record. We can use the same stochastic method of sequential block bootstrapping with that data and generate another suite of ensembles.

When you use the indexed sequential method, you basically generate the same number of ensembles as your data set. So in this case, we have 103 years. We have 103 traces. In this case, you get 1244 years. You get 1244 traces to use in your analysis.

The last step we did, we said, well, sometimes there's not a lot of confidence with the magnitude of information of paleo. In the Colorado River Basin, we're supposed to have about six different paleo reconstructions. The unfortunate part is all of those have different magnitudes in looking at those six different reconstructions.

One thing that we're able to see is, there's some agreement on the state amongst the reconstructions. That's the information about whether it's dry or wet in particular periods. So we want to capitalize on the strengths of that paleo record of state information, blend that with what our stakeholders are comfortable with, and that's the magnitude of the observed period.

But what it allows us generally to learn is that those contributions in the observed period captures sequences that were not seen in either the paleo or the observed but carry the traditional probability statistics of the paleo. So that gives you a much richer set of ensembles to look at and actually generates longer term droughts than were seen in either the paleo or the observed, and these drought sequences are actually a thing that's most critical to the Colorado River Basin, where you have these four years of storage capability in the basin. The sequencing is really what affects our analysis and decision variables of what we've seen.

So that's a methodology we developed during this process, and that methodology allowed our stakeholders to step from observed record to an in-between we're going all the way to paleo, and then also being able to go all the way to paleo.

So with our stakeholders, we found that taking these stepping methods had been a way to introduce them to new ideas and make them a little more comfortable, but you're still giving them concept basin hydrology for a long time but still stepping on them by adding new pieces to it.

This just is a graphic showing the idea of the different paleo reconstructions. We are just showing four that occurred at Lee's Ferry. This is the magnitude information, as you can see from different cores. They vary as far as the magnitude information. The Hildalgo record is pretty famous as the one with some pretty dire droughts in it.

A lot of this is just used the way you build your reconstruction method. This is basically a regression on tree ring chronologies, and depending on how you do that regression, you're going to get some different results. And that's really what we see here, is different methodologies. There are some different chronologies in there, but in general, this is from differing methodologies.

And here, we're showing state information. This is basically developed by showing the wet periods in black, breaking wet and dry from just a median of the paleo record, and then being able to start seeing what is the wet and dry sequencing and start to see some similarities across, while you may not see as much similarities in the magnitudes.

So that kind of motivated us to look at the stepping approach to start to see, could we blend paleo and observe, and this is the way we did it. It's basically using a Markov model to generate the sequence information, basically your wet and dry states, and then using a KNN traditional resampling to sample the observed record against the sequencing of state.

What this did is, it allowed us to develop a suite of scenarios for our sensitivity analysis. Here I'm just showing this to show you the differing valleys of the box of some basic statistics, means, standard deviations, skew, backward lag-1 correlation, maximum, minimum, and we have the direct natural flow record generated with that sequential block bootstrap method, the index sequential method. We have the index sequential method on the paleo data, both Meko's record and the Woodhouse record, and then we have this blended methodology from the two different paleo records.

And then there was also a stochastic method that was used in the draft environmental impact statement. It was basically a parametric stochastic method that was performed by a Dr. Salas out at Colorado State University, and it used a combination of a carbon model with a desired irrigation technique to move across the basins.

So what you can see here are the observed statistics in blue, and then you see the box part of the traces from each of these methods, and you'll notice that there's some variability across the methods. This paleo record shows reduced mean in both of these, while the paleo conditioning report has a mean pretty close to the observed, as seeing the magnitude you're drawing your information from.

You're not going to see differences too much in the statistics of the conditioning method until you start looking at frequency type statistics, things like drought spells. You're going to see some difference in backward lag correlation somewhat. Sometimes that can be a combination of sequencing and magnitude. But generally, you're just trying to see that with this, we're able to start to look at a richer variety of flows through our model. That's really what I want to try to bring about.

So what we're doing with these, we're moving these through our operation model. Our operation model is called Colorado River Simulation System. It's based in the RiverWare, a generalized river base modeling system. It's a product that was developed here at the University of Colorado. It's at a center that I'm based at here in Boulder, Colorado. And it is our primary tool for analyzing future river and reservoir conditions and the planning context, so it's basically our NEPA process. It's kind of a different process than the Corps goes through, as I'm hearing here today.

And we really stress, this is a projection model. It is not a predictive model. It's just trying to project what are the possibilities in the future and allow our stakeholders to understand the risks to use in different distribution variables. And what this allows us to do is look at a range of future scenarios and also to understand how our policy and rule sets might impact those decisions.

So here are some results from that particular scenario. This is Glen Canyon Dam, a 10-year release volume, and I'm just looking at the direct natural flow, which is not necessarily traditional, and the paleo, and you start to see this as a cumulative density function or a flow duration curve. You can start to see that there's some different results out of this decision variable based on the hydrology, and this is the kind of information we want to start bringing out to our stakeholders.

In the past, we only worked with this black line, so it looked like there wasn't much of a possibility of coming below about 78 million acre-feet, but once you fit in the other scenarios, the paleo or the blended, you start to see there is some probability of lower events occurring, and that's really where we want them to start considering.

The Colorado River Basin, of course, everyone knows, there's a lot of studies out there saying what these climate changes are going to be, and they're pretty variable. They go from a minus 6 percent decrease in the next 50 years to one study coming out at minus 45 percent. With a project that Robert Webb has been working on at NOAA, they've been able to narrow this range down, so now we're talking about minus 10 to minus 20 percent, but still, there's a range that we need to be able to incorporate into our work.

So some of the work we've been doing is looking at modifying this methodology -- instead of using the paleo record, let's use climate change and blend that with paleo. So we're taking the magnitude information from climate change, and we're actually blending that with paleo to generate sequences based on paleo but added to climate change information. And that allows us to capture some of the trends from the climate change while maintaining some of the sequencing and drought results from the paleo.

And the final one is, we only did that for small basins. We thought about doing this on the Gunnison and Missouri, a river basin on the Missouri River, and now we need to go to the full Colorado River Basin, so we have a project now that's working with Reclamation archival, which is peak levels, looking at the three ensembles, 16 GCMs, and having these be downscaled to 126 projections.

We moved then through the big hydrologic model out of University of Washington, and now we have 112 natural flow traces that we're preparing to move to our planning model, and what that's going to allow us to do is understand some of the sensitivities of what climate change, that has another planning hydrology, is going to do with our range of possibilities in the future.

And what I wanted to close with is this: These planning hydrologies can easily be developed to allow us to extend beyond the observed record which is what we're doing to date. We're just now stepping beyond that in the Colorado River Basin.

I don't want people to forget the importance of paleo record and the fact that it's got some key information, as far as frequency of events, as far as allowing us to understand the drought/surplus spells that are different than what we've seen in the current period, which is really critical information to bring to our analysis. It may be able to give us some information that we're losing in the GCMs, but there's methods that we can blend together.

And then the final projections really allow us to help understand the robustness of our system; and then presently, climate projections allow our stakeholders and decision makers to explore the sensitivity of the decision variables to a changing climate. Maybe you're going to not allow them to give a probability of what's occurring, but to allow them to understand the range of what's possible, and that's really critical for them to start considering as we continue to advance the climate science.

NOTE: *This is a transcript of the author's remarks at the workshop that has not been reviewed or edited by the author.*

Biography

James Prairie is a hydraulic engineer with the Upper Colorado Region of the Bureau of Reclamation. He has been working with Reclamation the past 9 years. Dr. Prairie leads the Colorado River Hydrology Workgroup whose objective is to position Reclamation's Upper and Lower Colorado Regions as a leader in water management and planning through the integration of quantitative climate variability and change in both mid-term operations and long-term planning. In addition to leading the workgroup Dr. Prairie's work activities include, hydrologic and salinity analysis, maintenance of historic and future projected natural flow and salt data and upper basin consumptive use for the Colorado River System. He also works in development and maintenance of mid-term operational and long-term planning models for the Colorado River.

Research interests include: stochastic streamflow and salinity generation with an emphasis in nonparametric techniques, advanced decision making techniques, and coupling of paleo, observed, and projected streamflows based on global circulation models (GCM). He has recently been leading a team that is developing natural flows throughout the Colorado River System based on 112 GCM projections. These flows will drive the Colorado River Simulation System (CRSS), Reclamation's long-term planning model and provide insights into reservoir operations under climate change.

RECLAMATION

Managing Water in the West

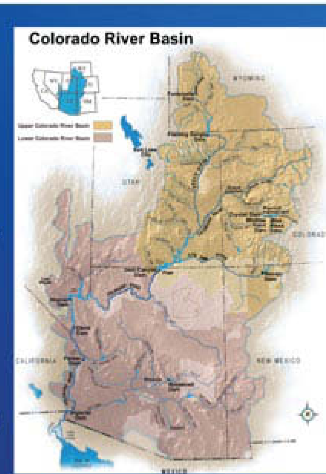
Planning Hydrology based on Blends of Instrumental Records, Paleoclimate, and Projected Climate Information

Workshop on Nonstationarity, Hydrologic Frequency Analysis, and Water Management
Boulder, CO
January 13-15, 2010

U.S. Department of the Interior
Bureau of Reclamation

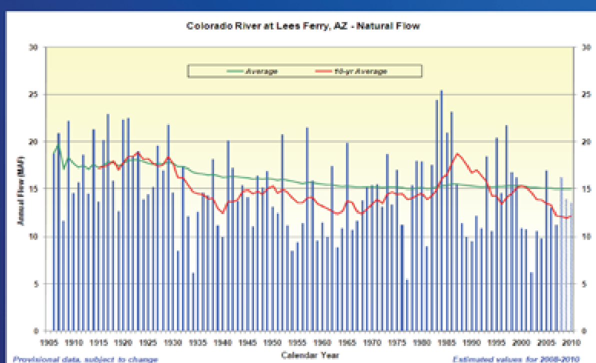
Colorado River Basin Hydrology

- 16.5 million acre-feet (maf) allocated annually
- 13 to 14.5 maf of consumptive use annually
- 60 maf of storage
- 15.0 maf average annual "natural" inflow into Lake Powell over past 103 years
- Inflows are highly variable year-to-year



RECLAMATION

Natural Flow
Colorado River at Lees Ferry Gaging Station, Arizona
Water Year 1906 to 2010



RECLAMATION

State of the System (1999-2010)

WY	Unregulated inflow into Powell % of Average	Powell and Mead Storage maf	Powell and Mead % Capacity
1999	109	47.59	95
2000	62	43.38	86
2001	59	39.01	78
2002	25	31.56	63
2003	52	27.73	55
2004	49	23.11	46
2005	105	27.16	54
2006	72	25.80	51
2007	70	24.43	49
2008	103	26.52	53
2009	88	26.40	53
2010*	78	25.99	52

* Inflow based on latest CBRFC forecast; storage and percent capacity based on Dec 2009 24-Month Study

RECLAMATION

Colorado River Drought

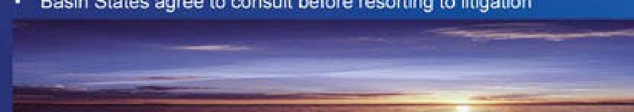
- 2000-2009 has been the driest 10-year period in the observed historical record (2008 through 2009 data are estimated)
- Projected 2010 April through July runoff is 78% of average
- Not unusual to have a few years of above average inflow during longer-term droughts (e.g., the 1950's)
- Tree-ring reconstructions show more severe droughts have occurred over the past 1200 years (e.g., drought in the mid 1100's)

RECLAMATION

Interim Guidelines[1]

A Robust Solution

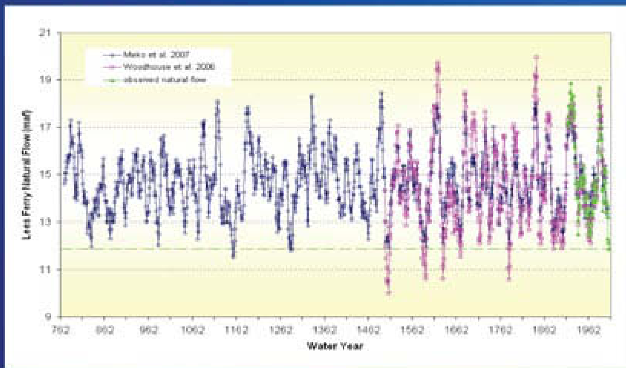
- Operations specified through the full range of operation for Lake Powell and Lake Mead
- Encourage efficient and flexible use and management of Colorado River water through the ICS mechanism
- Strategy for shortages in the Lower Basin, including a provision for additional shortages if warranted
- In place for an interim period (through 2026) to gain valuable operational experience
- Basin States agree to consult before resorting to litigation



[1]Issued in Record of Decision, dated December 13, 2007; available at http://www.usbr.gov/lc/region/programs/strategies.html

RECLAMATION

Annual Natural Flow at Lees Ferry
Tree-ring Reconstruction and Observed Record
10-Year Running Mean

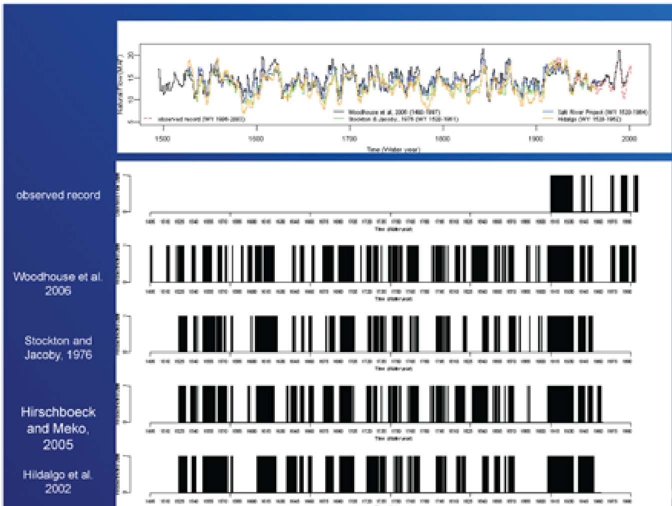


RECLAMATION

2007 Final EIS Hydrologic Sensitivity Analysis (Appendix N)

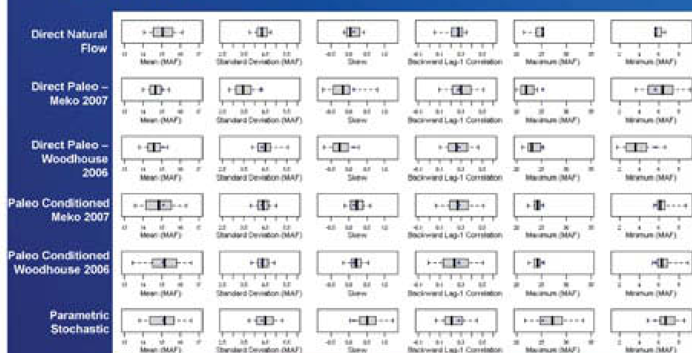
- 3 Hydrologic Inflow Scenarios Analyzed
  - Direct Natural Flow Record (DNF)
    - Indexed Sequential Method (ISM) applied to observed record (1906-2005)
  - Direct Paleo (DP)
    - ISM applied to paleo record (762-2005) *(Meko et al., 2007)*
  - Nonparametric Paleo Conditioned (NPC)
    - NPC applied to paleo record *(Prairie et al., 2008)*
  - These methodologies address uncertainty with regard to hydrologic variability but do not directly deal with climate change

RECLAMATION



RECLAMATION

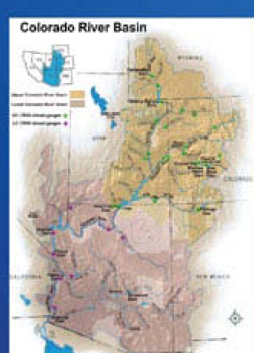
Comparison of Inflow Scenarios
"Box Plots"



RECLAMATION

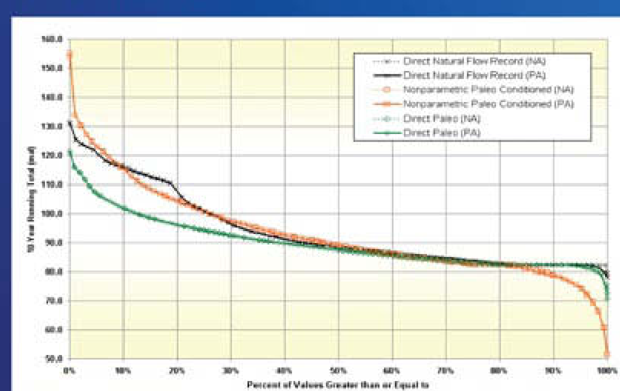
Colorado River Simulation System (CRSS)

- Comprehensive model of the Colorado River Basin
- Developed by Reclamation (early 1970s) and implemented in RiverWare™ (1996)
- Primary tool for analyzing future river and reservoir conditions in planning context (NEPA EIS)
- A projection model, not a predictive model
- Excellent for comparative analysis
- Gives a range of potential future system conditions (e.g., reservoir elevations, releases, energy generation)
- Simulates on a monthly timestep over decades
- Operating policy is represented by "rules" that drive the simulation and mimic how the system operates



RECLAMATION

Glen Canyon Dam 10-Year Release Volume
Water Years 2009-2060



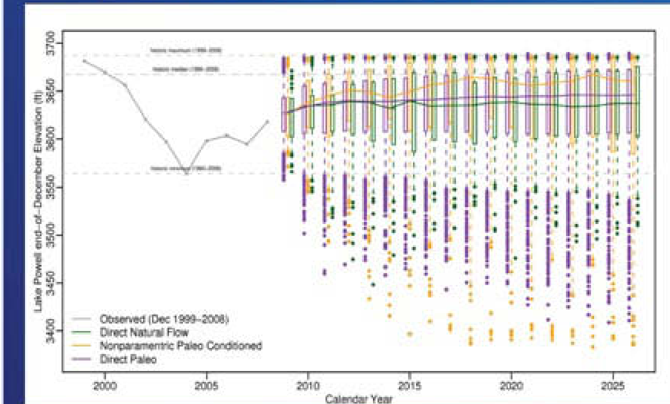
RECLAMATION

Moving Beyond the Observed Record

- Now include hydrologic inflow scenarios analyzed in Appendix N in official CRSS results
- Stakeholders requesting ability to perform simulations in CRSS with paleo data
- Accepted use of paleo data laying the ground work for incorporating climate change information in long-term planning
- Reclamation sponsored research using paleo to inform yearly sequencing blended with flow magnitudes generated by General Circulation Models

RECLAMATION

January 2009 CRSS Results: Lake Powell Elevations



RECLAMATION

"**Warming** of the climate system is **unequivocal**, as is now evident from observations of increases in global average air and ocean temperatures widespread melting of snow and ice, and rising global mean sea level."

IPCC (2007) Working Group 1
Summary for Policymakers

RECLAMATION

Climate Change Projections for the Colorado River Basin

- Changes in flow by mid-century

Study	GCMs (runs)	Spatial Scale	Temperature	Precipitation	Year	Runoff (Flow)
Christensen et al. 2004	1 (3)	VIC model grid (~8 mi)	~3.1°F	-6%	2040–49	-18%
Milly 2005, replotted by P.C.D. Milly	12 (26) (~100–300 mi)	GCM grids —	—		2041–60	-10 to -20% 96% model agreement
Hoerling and Eischeid 2006	18 (42)	NCDC Climate Division	~5.0°F	~0%	2035–60	-45%
Christensen and Lettenmaier 2007	11 (22)	VIC model grid (~8 mi)	+4.5°F (+1.8 to +5.0)	-1% (-21% to +13%)	2040–69	-6% (-40% to +18%)
Seager et al. 2007*	19 (49)	GCM grids (~100–300 mi)	—	—	2050	-16% (-8% to -25%)
McCabe and Wolock 2008	—	USGS HUC8 units (~25–65 mi)	Assumed -3.6°F	0%	—	-17 %
Barnett and Pierce 2008*	—	—	—	—	2057	Assumed -10% to -30%

Source: Ray et al., 2008

RECLAMATION

Comparison of Long-Term Planning Hydrologies based on Different Blends of Instrumental Record, Paleoclimate, and Projected Climate Information

(Brekke, Prairie, Pruitt, Rajagopalan, Woodhouse, 2008)
(funded from S&T, UC, GP)

Research Questions

1. How can paleoclimate and projected climate information be jointly and rationally incorporated into planning assumptions for water supplies, hereafter referred to as planning hydrology?
2. How would such a planning hydrology be similar to or different from planning hydrology developed to individually reflect paleoclimate or projected climate?
3. What implementation realities might influence choice among climate information sets when defining water supply planning assumptions for Reclamation studies?

RECLAMATION

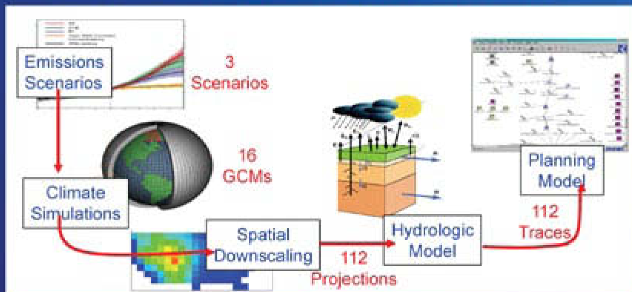
Combining paleo-reconstructed variability with projected future flows

Extension of existing framework

- **System State**
  - Paleo- reconstruciton
  - Meko et al, 2007
- **Magnitudes**
  - Replace observed record with projected climate data
  - Runoff magnitudes generated with CBRFC rainfall runoff model
- **Two Case Studies**
  1. Missouri River at Touston
  2. Gunnison River at Grand Junction
- **Four climate information sets**
  1. Null – state: observed magnitude: observed
  2. Alt 1 – state: paleo magnitude: observed
  3. Alt 2 – runoff projections direct from rainfall runoff model
  4. Alt 3 – state: paleo magnitude: runoff projections

RECLAMATION

Building Framework to Incorporate Climate Change Information in Long-Term Planning



- Joint research project with AMEC Earth & Environmental and Reclamation
- Anticipate CRSS results by February 2010
- Anticipate submitting peer reviewed publication in spring 2010

RECLAMATION

Closing Remarks

- Planning hydrologies can easily be developed that extend beyond the observed record
- Do not forget the importance of the paleo record
- Use climate change projection to better understand the robustness of your system
- Presently, climate projections allow stakeholders and decision makers to explore sensitivity of decision variables to a changing climate

RECLAMATION

Precipitation Nonstationarity Effects on Water Infrastructure and Risk Management

Jeff Yang, Environmental Protection Agency

Abstract

The non-stationary precipitation regime, as increasingly recognized, affects engineering basis and service functions of drinking water, wastewater, and stormwater infrastructures in urban centers. Small, yet significant rates of temporal precipitation change and diverse spatial distribution of its impacts over the contiguous U.S. dictate the technical and management approaches in infrastructure adaptation. Several engineering and management attributes such as the impending actions on aging water infrastructure assets, traditional engineering conservatism, and the adaptation cost, further add complexity to the discussion and development of a practical risk management framework. In this presentation, major precipitation nonstationarity effects are described in these dimensions, and the way in which adaptation and risk management can be incorporated into existing engineering practice is discussed.

Precipitation variability, particularly of extreme precipitation, is an expression of the evolving climate state and the relatively static local-regional climatic factors. The synoptic climate systems have been quantified in model simulations. In our research, the local-regional climatic factors are identified in a systematic investigation including wavelet and statistical analysis of long-range historical precipitation measurements obtained from 1207 climatic stations across the contiguous U.S. The precipitation datasets have registered the interactions between the synoptic systems and local-regional factors for the past >100 years. The analysis results led to the belief that the extreme precipitations, either the high-intensity or low-intensity, have strong periodicity regulated by local-regional factors in six delineated hydroclimatic provinces: (1) Florida and Southeast, (2) Lower Mississippi – Ohio River valley – New England region, or LONE, (3) Great Plains and Midwest, (4) Basin-and-Ranges, (5) West Coast, and 6) Great Lakes. At the first level, the provinces follow major physiographic provinces in the U.S. and each has its own characteristic variations in precipitation and perturbation in high frequencies. Figure 1 shows an example of high-frequency, high-intensity precipitation that clearly differentiates the Florida and Southeast province from the vast regions to the north and northwest. Arguably these local-regional climatic factors will interact with climate states in the future, a factor that deserves representation in downscaling efforts.

That extreme precipitation regulation differs in space has implications to hydraulic and water quality engineering of water infrastructures. The effect of nonstationarity on design storms is described by others in this workshop and discussed in recent publications (e.g., Mailhot et al., 2007). A series of "domino effects" on downstream hydrologic processes and water infrastructure operations can be readily discussed. In the remainder of this presentation, we will focus on the water quality aspect of the non-stationary precipitations in reference to drinking water plant operations. A scenario-based engineering analysis was conducted on the Greater Cincinnati Water Works' Richard Miller Treatment Plant that takes raw water from the nearby Ohio River. The high river flow, responding to high-intensity precipitation, is known to be responsible for high turbidity in surface water. For the plant, this increased level of turbidity is statistically related to high total organic content (TOC) and other general water quality variations. In a detailed process engineering analysis, we found the future scenarios will likely result in a large increase of disinfection by-product (DBP) in finished drinking water and lead to violation of the Safe Drinking Water Act regulations. A process adaptation using GAC filter in the Miller Plant would cost around $5 million/year for a 90% probability of compliance (Figure 2). Other levels of risk management are associated with different costs, as indicated by the cost cumulative density curve (CDF).

Our investigation so far has pointed to the need of water infrastructure adaptation to precipitation changes. The effects are tangible for all three types of infrastructure. It is important that the adaptation framework adapts to the current water engineering practices, for which a possible approach of iterative assessment-adaptation-monitoring procedure is discussed.

Biography

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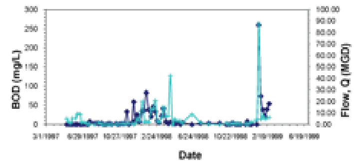
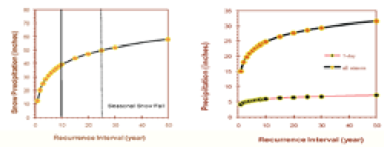
Jeff Yang is a physical scientist at EPA ORD National Risk Management Research laboratory, Water Supply and Water Resources Division. He leads the Water Resources Adaptation Program (WRAP). The WRAP research is focused on large-scale investigations of hydroclimatic changes and their impacts on drinking water, wastewater and storm water infrastructures, as well as water quality management programs. Another part of the research is the future energy production impacts on water resources. In the past 2 years, he and his team have published 8 journal articles, over 40 conference proceedings, and one EPA report on the climate change and water resources adaptations. Dr. Yang has been a part of the ORD climate change research program and an active participant of EPA's climate change research and regulatory initiatives. His research area and expertise include climate change related hydrology and water resources engineering. Before joined EPA in 2005, he was a principal consulting engineer in water projects in more than 20 states in the U.S. and overseas, and worked as a research scientist at the China Geological Survey before coming to U.S. in the 80s.

Water Infrastructure Engineering Challenges from Precipitation Variability

- Precipitation and snow projections in 25 years directly affect storage, treatment capacity, and hydraulic engineering;
- Stormwater discharges differ significantly among base flow and flows of varying precipitation events;
- Deicing-related BOD concentration in stormwater varies synchronously, with small off-sets of timing in peak loading;
- Both hydraulic flow and water quality loading in process design were difficult to predict. Both are related to precipitation and its variability.





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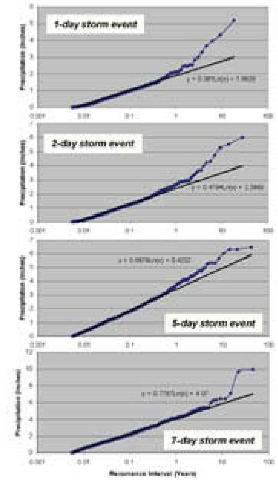
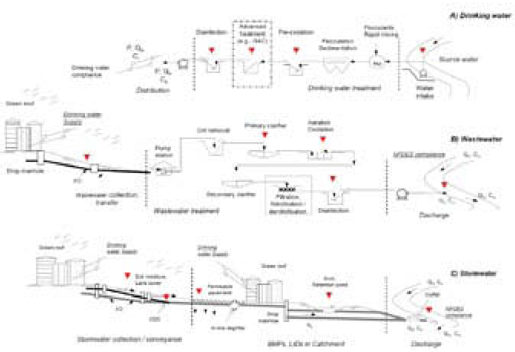
Accommodating Precipitation Variability in Hydrological Engineering

- Large safety factors in hydraulic engineering and related design parameters;
- Over-designed transfer and treatment facilities at capital and operational expense;
- The use of storage facilities – expensive for 30 Mgal tanks, and surface retention facilities;
- Still based on fundamental assumption of precipitation stationarity.



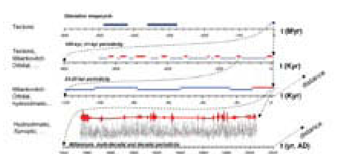
How Non-Stationarity Affects Water Infrastructure

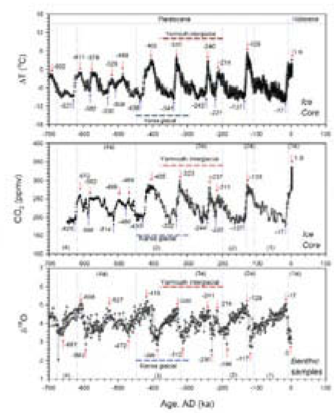


Stationarity and Non-Stationarity in a Perspective of Scales

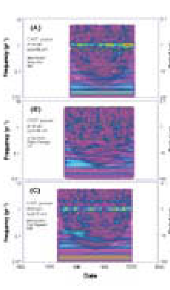
- Time and spatial scale variability important to understanding the non-stationarity
- Rate of change critical to evaluate and manage vulnerability and risk
- Precipitation-induced water quality equally important to water infrastructure sustainability

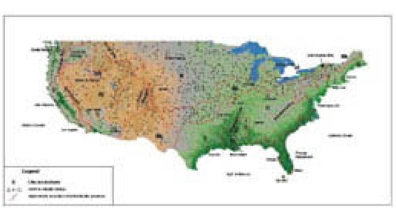
Yang and Goodrich (2009)





Understanding the Precipitation Variability

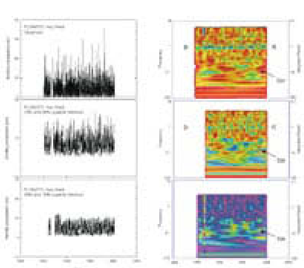


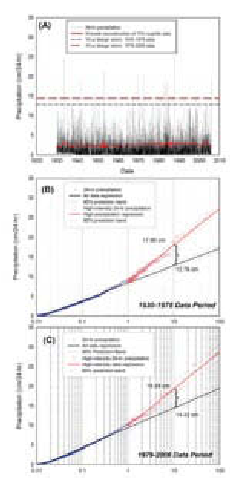


Bulletin 17-B

- High frequency (db~1 yr^{-1}) precipitations are broadly classified into Type-A and Type-B. Their spatial distributions coincide with major physiographical divisions;
- Local precipitation variability is the outcome of climate state and the effect of local-regional variables.

Understanding the Precipitation Variability and Its Implication

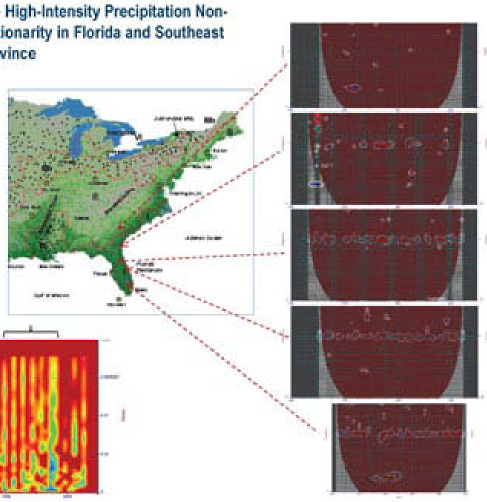


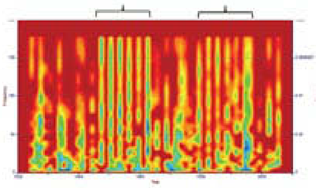


- Periodic occurrence of high-intensity precipitation events
- Because of non-stationarity, calculated design storm values depend on the data period used.

The High-Intensity Precipitation Non-stationarity in Florida and Southeast Province

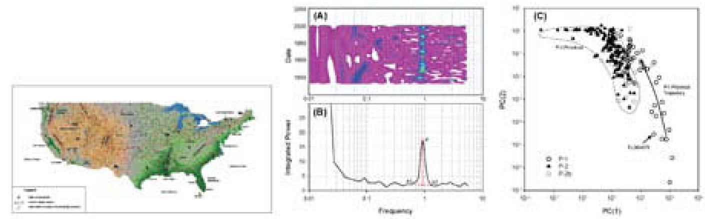
- The periodicity effects;
- The spatial distributions.



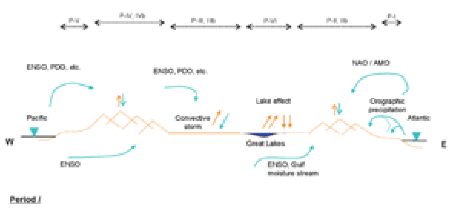


The Non-stationarity and Regional Distributions

- Non–stationary precipitation changes are likely region-specific;
- The interactions between future climate state and local-regional climatic factors have defined the past precipitation variability and will likely define it in the future;
- Regional/local factors were identified in the first-rate approximation for historical long-term (>100 yrs) precipitations. An example is shown below;
- The future non-stationary precipitation and its spatial distributions are the subject for further investigations.



Precipitation Variability and Climate Systems



Precipitation Variability = *Climate State* + Local / Regional Factors

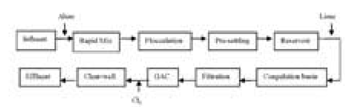
Infrastructure Adaptation – Miller Drinking Water Treatment Plant

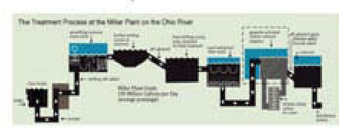
- Richard Miller drinking water treatment plant in Cincinnati is the first advanced GAC process in North America
- Design capacity: 220 MGD
- Ohio River as the source water
- GAC contactor with onsite regeneration
- Currently in compliance with drinking water standards

Table 10.2 Miller WTP Unit Process Design Parameters

Unit Process	Volume, m^3	T_{10}*, min
Rapid mixing	31.8	2
Flocculation basin	7342.9	14
Pre-settling	8440.6	14
Reservoir settling	1411605.0	1,728
Coagulation basin	58416.0	144
Filtration	9352.0	4
GAC Contactors	9311.1	–
Clear-well	107116.0	77

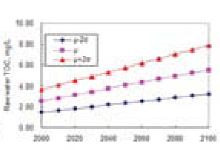
– data not available.
(Data source: USEPA ICR database).

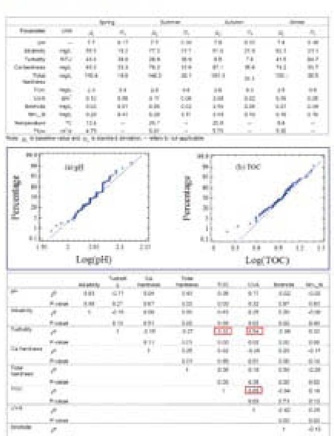




Infrastructure Adaptation – Miller Drinking Water Treatment Plant: TOC variation and precipitation regime

- Statistical correlations revealed from ICR data for six WTPs at Ohio River
- Turbidity are statistically correlated with TOC and UVA
- Monte-Carlo simulation for occurrence probability of TOC levels
- TOC and UVA are disinfection by-product (DBP) precursor and indicator
- Scenario analysis conducted for future water quality at intake

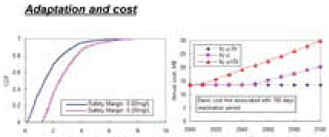




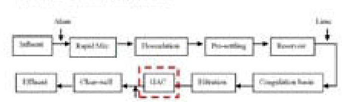
Infrastructure Adaptation – Miller Drinking Water Treatment Plant: Process engineering

- Water quality parameters simulated for future scenarios using the modified EPA Water Treatment Plant (WTP) model
- TOC and DBP standards are currently met in baseline conditions
- Simulations indicate that 55% probability in TOC and DBP violation in future scenarios of TOC increases in source water
- Adjustment to GAC regeneration operation is practical for adaptation
- In 2050, the annual operation cost of GAC adaptation engineering is $14.0 million. Or $0.18/1000gal at full capacity, and $0.35 at the 50% capacity

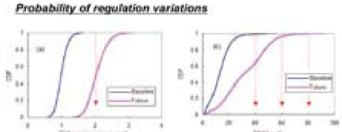
Adaptation and cost



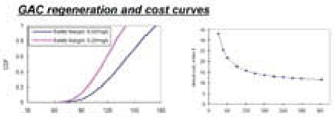
Modeled treatment process



Probability of regulation variations

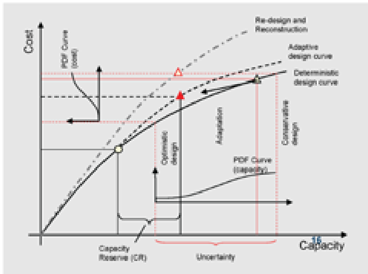


GAC regeneration and cost curves



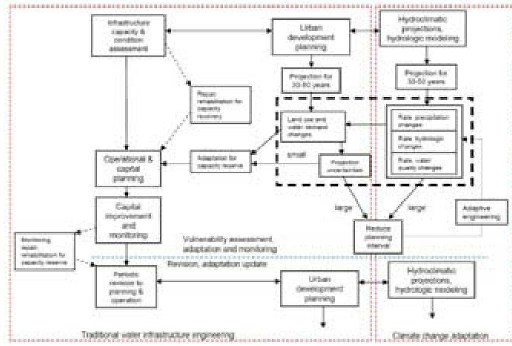
Water Infrastructure Adaptation and Risk Management

- Tangible change with large uncertainties
- Small rate of changes, ample time for adaptation, but large system inertia and momentums
- Engineering cost, conservatism, and proactive adaptation



Office of Research and Development

Muddling Through for Imperfect Knowledge of Precipitation Non-stationarity



Closing Thoughts

- Non-stationary precipitation affects the service functions of stormwater, wastewater and drinking water infrastructures.
- The non-stationarity of high-intensity (or low-intensity) precipitation has regional distributions, and varies with time
- Hydroclimatic province delineation helps to isolate the local / regional climate factors
- Adaptation planning and engineering must consider the non-stationarity and its region-specific uniqueness
- Coordinated efforts needed to improve the precipitation projection accuracy and quantify the uncertainty for risk management in climate change adaptations

Thank You!

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United Kingdom Climate Change Adaptation

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Abstract

Public water supplies in England and Wales are provided by around 25 private-sector companies, heavily regulated by an economic regulator (Ofwat) and and environmental regulator (Environment Agency). As part of the regulatory process, companies are required periodically to review their investment needs to maintain safe and secure replies, and this involves an assessment of the future balance between water supply and demand. The water industry and regulators have developed an agreed set of procedures for this assessment. Climate change has been incorporated into these procedures since the late 1990s, although has been included increasingly seriously over time. In the last assessment, companies were required explicitly to plan for a defined amount of climate change, taking into account climate change uncertainty. A "medium" climate change scenario was defined, together with "wet" and "dry" extremes, based on scenarios developed from a number of climate models.

The water industry and its regulators are now gearing up to exploit the new UKCP09 probabilistic climate change projections – but these pose significant practical and conceptual challenges. This paper outlines how the procedures for incorporating climate change into water resources planning have evolved, and explores the issues currently facing the industry.

Introduction

A number of modelling studies (e.g. Arnell, 2004; Wilby et al., 2006a; Fowler et al., 2007; Manning et al., 2009) have indicated that, under most climate change scenarios, river flows in British rivers could be significantly reduced for at least a portion of the year. These changes are particularly large in the south and east of England, which are already under locally-severe water resources pressures.

Climate change has been explicitly considered by water resources managers in England and Wales since the mid 1990s, following a series of major droughts (Arnell & Delaney, 2006), although the way it has been treated and the types of decisions that have been taken have changed over time. This paper reviews the ways climate change has been incorporated into water supply planning in England and Wales, discussing why it has evolved and the sources of information used. Context is extremely important, so the paper begins by giving an overview of the water resources planning process in England and Wales (procedures are different in the other parts of the United Kingdom).

The Context: the Structure of Water Resources Planning in England and Wales

Public water supplies are currently provided by around 25 private-sector companies, with vastly varying sizes and patterns of ownership. Some are wholly-owned subsidiaries of multinational utility companies, some are parts of companies delivering a range of utility services, some are owned by shareholders and listed on the London Stock Exchange, and one is set up as a not-for-profit enterprise. The companies fall into two broad categories, reflecting their historical evolution. One group, comprising ten companies, is responsible for both public water supplies and for collecting and treating sewage effluent. These companies are descendants of public water authorities, and operate within boundaries defined by watersheds (England and Wales is essentially divided into ten watersheds or groups of watersheds). The remaining companies are responsible just for providing public water supplies (they are known as "water-only companies") to customers within specific areas. These areas – which of course all fall within the ten major watershed regions – are rarely defined on the basis of hydrological units, and many follow old administrative boundaries. A given watershed may therefore contain a number of water supply companies (but only one company collects and treats effluent), and a given water-only company may supply customers in a number of separate – but typically adjacent – watersheds.

The companies together abstract around 17,000 megalitres of water per day (Environment Agency, 2008) a total which has changed little over the last ten years. Approximately half is supplied to households. Average household use was 148 litres/person/day in 2007-8 (Environment Agency, 2008) but varies regionally from less than 130 to more than 170 litres/person/day. Only around 30% of households pay for water through a meter; the remaining 70% pay a flat annual rate based on property value. Around 20% of public water supplies go to industry (all metered), and reductions in industrial demands have been offset by increases in total household demand. A small proportion of the remaining 30% of public water supplies goes to agriculture – though mostly not for irrigation – and the rest is lost as leakage through the distribution system. Farmers directly abstract only a small volume of water nationally for spray irrigation – less than 1000 megalitres – but this is concentrated in the drier east of England and during the summer months, so locally direct abstraction by farmers can be greater than abstractions for public water supply.

Across England and Wales as a whole, total abstractions for public water supply, direct abstractions by industry (less than a quarter of public water supply abstractions) and direct abstractions by agriculture represent around 10% of available freshwater resources (Environment Agency, 2008). However, this ratio varies considerably, and in the populous, and relatively dry, south east of England approximately 22% of average annual runoff is abstracted. In approximately 33% of catchments, mostly in the south and east of England, abstractions are deemed to be “unacceptably” high (Environment Agency, 2008).

The private-sector water supply companies are heavily regulated by two main regulators. An economic regulator, Ofwat, gives companies a long-term licence to operate, sets general performance standards, and controls prices to customers. An environmental regulator, the Environment Agency, issues licences for individual abstractions (and effluent returns), and monitors the environmental performance of water supply companies (a third regulator monitors drinking water standards). The Environment Agency provides a framework for the management of water resources through a hierarchy of national, regional (the 10 major watersheds) and local catchment-scale water resources strategies. These set general water management principles, seeking to safeguard the interests of all users of water resources – including the environment – and provide the framework for decisions on specific abstraction requests made by water supply companies. The Environment Agency’s national and regional strategies were most recently revised in 2009 (Environment Agency, 2009), amending strategies produced in 2001 (Environment Agency, 2001).

Both regulators, and particularly the Environment Agency, are strongly influenced by higher-level agencies. The Department for the Environment, Food and Rural Affairs (Defra) sets the high-level water resources policy for England and Wales (most recently in the strategy document Future Water (Defra, 2008)). The European Union Framework Water Directive, which entered into force in 2000, requires all European Union members to ensure that all water bodies reach “good” ecological status by 2015, and basically sets out a river basin management framework to deliver this. The Environment Agency’s water resource planning structure is driven by the Framework Water Directive, although in practice many of the measures were already in place before the Directive came into force.

A major role of the economic regulator, Ofwat, is to regulate the prices the water companies can charge their customers. Ofwat does this by undertaking Periodic Reviews every five years. The Third Periodic Review was undertaken in 2004 (PR04), covering the period 2005-2010, and the Fourth Periodic Review took place in 2009 (PR09): this covers 2011 to 2015. The Periodic Review requires companies to prepare Business Plans, detailing their proposed expenditure and investment, and Ofwat sets price limits accordingly (in practice by imposing a lower price increase than the companies originally propose). A key part of a company’s Business Plan is its Asset Management Plan (AMP), which specifies the investments the company proposes in order to maintain security of supply and water quality standards. In the first two Periodic Reviews most of these investments were to raise water quality standards, but since the Third Periodic Review, an increasing proportion of these investments have gone on water supply.

This regulatory structure appears complex, but it is important to describe all the components, because the structure determines why and how climate change is incorporated into water resources management plans.

Water Resources Assessment Procedures

A company’s Asset Management Plan is driven by, amongst other things, the company’s Water Resources Management Plan (WRMP). The company’s WRMP must be approved by the Environment Agency, and therefore – at least in principle – be consistent with the Environment Agency’s national and regional water resources strategies and catchment abstraction management plans. Since 2003, these WRMPs have been statutory requirements; prior to then they were voluntarily produced by the companies. The WRMP sets out the companies plan for the following 25 years.

Company Business Plans, Asset Management Plans and Water Resources Management Plans are reviewed by the Environment Agency and Ofwat in the Periodic Review process. It is therefore essential that each is based on a set of agreed procedures and methodologies. The Water Resources Management Plans include assessments of the available supplies and projected demands within supply zones, and the procedures for making these assessments are published by the Environment Agency in Water Resources Planning Guidelines (published in 2003 for PR04 (Environment Agency, 2003) and in 2007 for PR09 (Environment Agency, 2007). These guidelines "provide a framework for water companies to follow in developing and presenting their water resources plans", rather than a set of explicit instructions, but companies are required to justify any departures from the guidelines. The guidelines are drawn up in consultation with Ofwat and the water companies (and water industry representative bodies), and effectively represent an agreed "best practice". They include technical annexes, outlining specific techniques to be used, and guidance on how to use the information.

Fundamentally, the technical guidelines require the companies to estimate current and future available water supplies, current and projected demands, and a "safety factor", for each water resource zone. A water resource zone (WRZ) is the fundamental planning unit within a water company, and is managed as a single unit; there are 80 WRZs in England and Wales. WRZs contain a mixture of different supply sources, all of which can provide supplies to anywhere within the zone. Most WRZs also have imports and exports of raw or potable water. The details have varied over time, but in effect for each WRZ water companies must calculate the following balance:

$$\text{TWAFU} + \text{headroom} > \text{Demand}$$

"TWAFU" is the total water available for use in the WRZ, and "headroom" can be seen as a safety factor.

TWAFU comprises a number of components, which can broadly be grouped into four categories. The first is the deployable output (DO), which is the amount which can be supplied from all sources within the WRZ during a "dry year". This is defined differently in different WRZs, but is typically either the deployable output over a critical period for a specific return period or, much more frequently, during an historical drought. The historical drought used varies between WRZs, depending on system sensitivities, but is often one of either 1933-34 or 1975-76. The second group of components represent changes to DO over time because of, for example, the introduction of new sources, closure of sources, or changes to environmental obligations. The third group represents an allowance for operational losses, and the fourth represents the net import of raw and potable water.

Headroom is a buffer between supply and demand designed to cater for specified uncertainties. The first standardised headroom methodology was introduced in 1998 (UKWIR, 1998) for the second Periodic Review, and an enhanced methdology was produced in 2003 (UKWIR, 2003). Both methodologies essentially define a set of sources of uncertainty, and allocate scores to these sources. These scores are then converted to a percentage figure to be applied to DO. Sources of uncertainty include data uncertainty, vulnerability of licences to pollution, reliability of inter-basin imports and reliance on single sources. The two headroom methodologies differ largely in terms of how they allocate scores to the different sources of uncertainty and combine them to produce the total headroom allowance; the enhanced methodology combines probability distributions describing the different sources of uncertainty, rather than using simple scores read from a look-up table.

Recommended procedures for estimating future demand by WRZ have varied over time, and in PR09 companies were given greater flexibility in approach.

Incorporating Climate Change into Water Resources Planning

Climate change has been incorporated into water resources planning at three levels, in different ways in each periodic review.

At the highest level, government and the regulators have required water companies to consider climate change. As far back as 1996, government policy "urged" water companies to consider climate change in their planning (Department of the Environment, 1996), following significant droughts in 1994 and 1995. This top-level encouragement was further strengthened in the 2002 and 2009 government policy documents. In Future Water (Defra, 2009), the government stated that "in (water resources management plans) water companies must examine their supply options strategically and innovatively and take into account the best available information about changes in climate, population and water demand." The Environment Agency water resources strategies in 2001 and 2009 both specifically require companies to take climate change into account, and the Water Resources Planning Guidelines specify how – as outlined below. Perhaps rather surprisingly, the procedures for the implementation of the European Union Water Framework Directive make no reference to climate change (Wilby et al., 2006b).

In practice, climate change has been incorporated into company water resource management plans differently in the Second, Third and Fourth Periodic Reviews.

The Second Periodic Review (1999)

The Second Periodic Review was completed in 1999, with work starting in 1997. As part of this process, the Environment Agency and water companies (represented by the industry body UKWIR) initiated the development of a simple methodology to enable companies rapidly to estimate the potential effects of climate change on water supplies. In principle, the effects of climate change on river flows and groundwater recharge are best estimated by applying climate change scenarios to observed baseline weather data, and simulating river flows and recharge using a calibrated and validated catchment or recharge model. In practice, there were a number of problems with this approach in 1997. First, there were no agreed climate scenarios. Second, models were available for very few catchments or aquifers. Third, calculations had to be completed for several hundred separate sources – and fourth, little time was available. A rather simple method was therefore developed , involving the construction of regional average monthly "flow factors" to be applied to observed flow data to rapidly produce a time series representing the effect of climate change. These flow factors were essentially derived by applying scenarios in around 60 catchments which did have hydrological models, calculating changes in mean monthly runoff, and constructing regional averages from the 60 original catchments (UKWIR, 1997). The limitations of the approach were noted – the method only works because climate change does not affect the timing of river flows in the UK, where snowmelt is rarely an issue – and companies were urged to use rainfall-runoff models whereever possible. An even simpler set of annual factors was constructed to perturb observed annual groundwater recharge. The water companies initially wanted climate change factors for "the" climate scenario. Following discussions, the companies agreed to consider four climate scenarios, and these were constructed from the output from a set of climate models available at the time.

The first version of the headroom methodology was also being constructed in 1997, and climate change was included as one of the factors affecting both supply-side and demand-side uncertainty (UKWIR, 1998). The headroom score for supply-side effects of climate change effectively represented the range between the four estimates of the effect of climate change, and translated into a headroom factor due just to climate change of between 1 and 4%, depending on the total headroom score. The effects of climate change on demand were to be estimated using the results of a study for the Department of the Environment (1997); the effects, however, were typically small.

In practice, the water companies only included the effect of climate change on water supply in their water resources plans for the Second Periodic Review through the headroom score, and virtually all used the "flow factors" rather than the hydrological modelling approach. Climate change did not therefore significantly affect company plans or decisions, but the foundations for a methodology had been laid. This methodology was easy to use (but had an "advanced user" variant), and explicitly accounted for the effects of uncertainty in potential future climate change.

The Third Periodic Review (2004)

Two main developments occurred between the Second and Third Periodic Reviews. First, the Environment Agency Water Resources Planning Guidelines (Environment Agency, 2003) became more explicit. They not only specified how climate change should be included in the calculations of available resources, but also moved on the another level by specifying how the results should be used. The second development was the production of a set of "industry-standard" climate change scenarios – the UKCIP02 scenarios (Hulme et al., 2002), recommended for use in climate change impact assessments across all sectors.

The "flow factors" produced for the Second Periodic Review were therefore revised using the UKCIP02 scenarios, with the addition of "wet" and "dry" scenarios to extend the range of uncertainty further than implied by the UKCIP02 scenarios alone (UKWIR, 2003). Again, companies were recommended to use hydrological models wherever feasible to estimate the effects of climate change – but few did.

The Water Resource Planning Guidelines for the Third Periodic Review (Environment Agency, 2003) presented guidance on using these new flow factors in a supplementary note. This suggested just using the medium scenario – because the range between the four scenarios was generally small – but also required calculating the climate change contribution to headroom. Effects of climate change on demand were to be estimated using either the 1997 Department of the Environment study or a more detailed analysis undertaken by Downing et al. (2003).

The next level of guidance specified what companies should do once the climate change effect was determined for a resource zone:

- If it is clear that the impact of climate change makes little or no difference to activities before 2030, the company may state this and does not need to change its water resources plan;
- If the impact of climate change makes little difference before 2020 but could to 2030 consideration must be given to the timing of the necessary investigations;
- If the impact of climate change is great enough to require changes to the water resources plan before 2020, the company should consider the further investigations and analysis that will be needed.

The allowance for climate change should be made either explicitly or in headroom depending on the outcomes referenced above.

In practice, whilst the medium scenario of climate change was estimated to lead to reductions in deployable output in some resource zones of up to 10-12% by 2030, climate change did not figure strongly in company Water Resources Management Plans or Business Plans (Arnell & Delaney, 2006). Climate change was combined with other drivers of change and, over the planning horizon was less significant than these other drivers. Ofwat, in its final determination of prices, explicitly made no allowance for extra investment to address climate change (Ofwat, 2004), and indeed stated that "it is neither possible nor sensible to set out detailed requirements to cater for these eventualities now." The Environment Agency, in its review of the company plans, requested that several companies continue their assessment of the effects of climate change (Environment Agency, 2004).

The Fourth Periodic Review (2009)

By the time of the Fourth Periodic Review, no new climate scenarios had been published but there was an increasing concern in the water industry that the potential range in change as characterised by the UKCIP02 scenarios and the 2003 "Flow Factors" was too narrow. The next generation of UK climate scenarios were scheduled to be published in 2008 (in the event they were published in 2009 as the UKCP09 climate projections), but this would be too late for them to be used for the Fourth Periodic Review.

In preparation for the Fourth Periodic Review, a wider range of climate scenarios was therefore constructed based on the outputs from a set of climate models as assessed in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. From these, three scenarios were defined, representing a "mid" change (in practice close to the change as projected under UKCIP02) together with wet and dry scenarios spanning a greater range than that defined for the Third Periodic Review. Again, it was recommended that companies use hydrological models rather than "flow factors".

The Water Resources Planning Guidelines for the Fourth Periodic Review (Environment Agency, 2007) include very specific guidance on incorporating climate change on supplies in an annex (Arnell & Reynard, 2007). This guidance is more explicit than for previous reviews, and state that companies should include the "mid" estimate of climate change impact directly in their estimate of deployable output, and include the range between the wet and dry scenarios in headroom, using either the original or enhanced methodology. Another change was the requirement to estimate deployable output, and hence the effect of climate change, for every year in the planning period between the base year (2009/10) and the final planning year (2034/35). A procedure therefore had to be developed to allow the interpolation of the climate change effect on deployable output (and headroom range) from the end of the available record to 2034/35. It was not appropriate to include steps in this progression, as this may artificially influence investment profiles. The climate change scenarios are defined relative to 1961-1990 (equivalent in practice to 1975), and of course since 1990 there have been almost 20 years of observed experience. The estimate of deployable output using data extending to 2008 (the last year for which data were generally available to companies) may be quite different to the estimate for 2008 based on interpolating between 1975 and 2034/35, due to natural year-to-year variability. A rather empirical method was therefore develop to blend recent experience with the underlying trend between 1975 and 2034/35 to produce smooth trajectories of change in deployable output.

For the Fourth Periodic Review, unlike the previous review, all companies were therefore "guided" to include a climate change allowance in their central planning estimate of deployable output. The Water Resource Planning Guidelines also stated explicitly how companies should use the climate change information, using the same guidelines as in the Third Periodic Review but with dates shifted by five years. Effects of climate change on demand were to be estimated using either the 1997 Department of the Environment study or a more detailed analysis undertaken by Downing et al. (2003). Ofwat also, for the first, time, explicitly required companies to consider climate change (Ofwat, 2008).

In practice, most companies in most resource zones used the flow factors rather than hydrological models to estimate the effects of climate change (Charlton & Arnell, 2010). For a small minority of water resource zones, companies did not explicitly include a climate change allowance, either because it was very small or, in one case, because the company found that different modelling techniques gave different changes for the same scenario. No company included a "positive" effect of climate change (i.e. an increase in deployable output), and the climate change effect was set to zero if the mid scenario implied increased deployable output. This reflects a strong degree of risk aversion amongst water supply companies. Charlton & Arnell (2010) estimated, from company plans, that the effect of climate change under the mid scenario totalled just over 500 Mld by 2035, or approximately 3% of total deployable output in England and Wales. However, this reduction was unevenly concentrated – more than half is in south east England – and in some resource zones could be greater than 10% of deployable output. Climate change was found to be by far the largest single component affecting supply, and of a similar magnitude to the increase in demand across the whole of England and Wales. The relative magnitudes of changes in demand and climate change effects on supply, however, vary between resource zones. The range in change between the wet and dry scenarios was found to be extremely large in some resource zones, and companies noted that this affected their attitudes towards new resource requirements.

In contrast to the previous assessment, companies placed a greater emphasis on climate change in the Fourth Periodic Review (Charlton & Arnell, 2010), and companies proposed spending approximately £1.5 billion before 2015 to address effects of climate change on supply (Ofwat, 2009). However, in its determination on prices, Ofwat (2009), did not allow for any significant climate change expenditure because "the evidence available to companies when they prepared their final business plans was out of date and soon to be superseded by the UKCP09 scenarios" (p61). It did allow companies to undertake further analysis using the UKCP09 scenario analysis, and promised to take into account in an interim determination any expenditure companies may need before the end of the review period (2015) to deal with the impact of climate change.

New Developments: Coping with Probabilistic Climate Scenarios

The UKCP09 climate projections, published in 2009 (ukcp09.defra.gov.uk), are fundamentally different to the preceding UKCIP02 scenarios. The UKCIP02 scenarios essentially provide three climate scenarios (four after 2050, when the medium scenario splits), to which "wet" and "dry" scenarios have been added. The UKCP09 climate projections, in contrast, are expressed in probabilistic terms. These climate projections can be used to produce not three or four estimates of the impact of climate change, but many thousands, from which a "probability distribution" of impacts can be constructed. This is apparently attractive, as it enables water resources managers to adopt a risk-based approach to coping with climate change uncertainty. Such an approach has been increasingly advocated (e.g. Palmer et al., 2005; Murphy et al., 2007; Tebaldi & Knutti, 2007), and many resource managers in the UK and elsewhere are attracted to the concept. Indeed, Ofwat (2009) specifically require companies to use UKCP09 projections to assess the effects of climate change on supplies.

There are, however, three major challenges with a probabilistic approach as represented by UKCP09. First, the probabilistic projections are themselves uncertain, as different ways of constructing probabilistic projections can give different results, and because the projections are typically conditional on some underlying assumptions. Second, a probabilistic approach tends to reduce climate change uncertainty to one number – a quantile taken from the probability distribution of potential impacts – and this can encourage a "predict-and-provide" approach rather than a more robust "hedge-and-adjust" approach to uncertainty. Third, probabilistic projections can be difficult to apply in practice. Instead of applying three or four scenarios, it may be necessary to apply several thousand. This will likely tax many operational water managers – especially because climate change is only one of a number of factors that may need to be considered. A practical way of using information from UKCP09 is therefore urgently needed by water companies in England and Wales if they are to satisfy the regulator Ofwat and attract investment to implement climate change adaptation measures.

Whilst there is an increasing demand for more "robust" ways of characterising the uncertainty in climate change projections, particularly now that the estimated impacts of climate change may begin to appear within resource planning horizons, there are clearly major practical and conceptual challenges involved in going down the probabilistic route.

Conclusions and Implications

This paper has given an overview of the way climate change is incorporated into water resources planning in England and Wales. Climate change has been included within plans since the mid 1990s. The broad approach has stayed reasonably consistent since 1997. It has been based around three or (in the first assessment) four scenarios, with great emphasis placed on a central scenario, and has also largely used very simple "flow factors" to apply the scenarios. The details of both the methodologies and the way the information is used have changed over time. It is possible to draw a number of general conclusions from the case study of England and Wales.

First, the specifics of how climate change can be incorporated into water resources planning is dependent on the institutional context. The overall structure of the approach used in England and Wales is driven by the strong roles of the regulators and the need to develop "best-practice" approaches to enable comparisons between companies. The details of the approaches adopted are strongly influenced by the information base available to the water companies (i.e. their widespread lack of models), the diverse and large range of locations for which assessments are needed, and – crucially – the existence of standardised climate scenarios. A major question – not directly addressed in this paper – is the extent to which the institutional context constrains the ability of water companies to adapt effectively to climate change (there is an argument, for example, that the relatively short-time horizon of the Ofwat Periodic Reviews hinders the development of long-term investment strategies, and the current funding arrangements in England and Wales pass the total costs of adapting to climate change onto water supply companies and their customers).

Second, any methods that are developed to account for climate change need to be consistent with water resource assessment and management methodologies. They need to require a proportionate effort, and to build upon existing methods and tools.

Third, methods need to evolve over time, as the requirements of water managers and the potential availability of information changes. For example, two factors encourage a step-change in the methodology applied in England and Wales before the next assessment (by 2014). First, the availability of probabilistic projections has stimulated considerable interest in alternative ways of representing uncertainty, but it is currently not clear how best to make this step. Second, a concern with the trajectory of change between now and the planning horizon – 2035 or 2040 – means that some methodology needs to be developed that can reconcile the effects of year-to-year climatic variability with the underlying trend(s) associated with a gradual change in climate.

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Biography

Nigel Arnell became director of the Walker Institute at the University of Reading in 2007, moving from the University of Southampton where he had been head of the School of Geography since 2003. He has been working on climate change impacts in the water sector since the late 1980s, initially at the NERC Institute of Hydrology.

His research focuses on two scales – the catchment and the global scales. At the catchment scale, Professor Arnell's research is particularly focused on the use of climate information to inform adaptation decisions. He led the development of the methods used by the UK water industry to incorporate the effects of climate change on water supply reliability, and co-wrote the guidance on incorporating climate change into water resource management plans for PR09. He has used UKCIP98, UKCIP02 and UKCP09 climate projections, and developed his own scenarios for hydrological impact assessments. Professor Arnell is part of an Environment Agency project examining the use of UKCP09 climate projections for the Environment Agency. At the other end of the spectrum, Professor Arnell leads research into the global scale implications of climate change for the distribution and availability of water resources. He is currently heavily involved in the DECC/Defra AVOID project, with particular responsibilities for leading assessments of the effect of climate policy on the global-scale impacts of climate change.

Professor Arnell has been involved in the IPCC since the second assessment report; he was coordinating lead author (i.e. leader) for the water chapters in the second and third reports, and was a lead author for two chapters and the Summary for Policymakers in the fourth assessment report. He is also an author of the IPCC's Technical Report on Climate Change and Water (finalised in April 2008), and is currently a lead author for the IPCC Special Report on Extremes.

The supply-demand balance

Walker Institute

TWAFU + Headroom > Demand

Total Water Available For Use
- deployable output
- transfers
- operational uses

Demand
- peak or average

Headroom
- uncertainty "safety factor"

"50-year" drought (annual or critical period)
"drought of record"

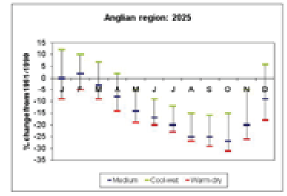
University of Reading

Evolution...

Walker Institute

2003 (PR04)

- use three scenarios (2025)
- UKCIP02 medium+ wet/dry variants
- climate change "considered" in addition to baseline resource estimates



Thames / London:
11-13% reduction in reliable yield by 2025
(relative to 1961-1990 climate)

University of Reading

2008-9: PR09

Walker Institute

Three scenarios for 2035 relative to 1961-1990

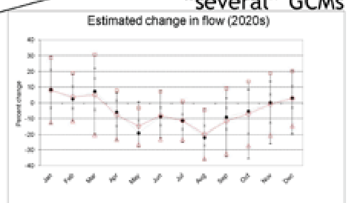
- mean / high / low

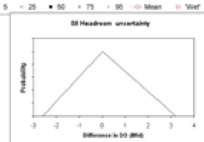
Based on scenarios constructed from "several" GCMs

Use mean scenario for baseline resource estimate

Interpolate change in DO from 2006 to 2035

Account for range in headroom





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Application of the method...

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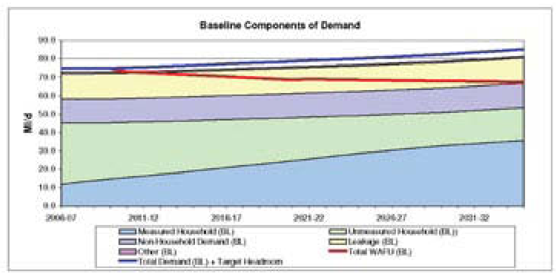

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Results

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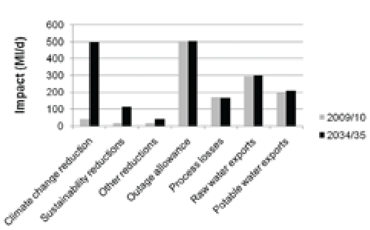
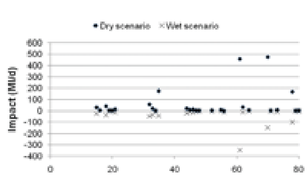


England and Wales total effect



Resource-zone level uncertainty effect

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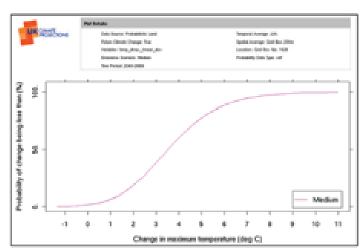
Next steps: risk-based approaches

Walker Institute

UKCP09 probabilistic projections released in summer 2009



So why don't we use a risk-based approach?

University of Reading

International Perspectives on Nonstationarity

A World Bank View on Climate Change Adaptations

Ken Strzepek, World Bank

Abstract

The World Bank recognizes water as a key affected sector, and potential strategies for adapting to climate change have become central to the dialogue on water policy reforms and investment programs with client countries. In order to support this process and future World Bank initiatives, the Water Anchor is undertaking a two-year AAA (FY08-09) on Water and Climate Change. The main objective of the AAA is to provide analytical, intellectual and strategic support to Bank operations and client countries in order to assist them in making sound water investment decisions that account for climate variability and change. The output of this AAA will be a series of reports that will address a number of key questions, such as: (i) what are the impacts of climate variability and change on water systems, both natural and engineered; (ii) what are adaptation strategies to reduce vulnerability of water systems to these impacts; (iii) how can the Bank assist client countries in making informed decisions regarding adaptation options in their water investments. A brief description of the Pilot Programme for Climate Resilience and other adaptation activates in the Regional Investment Activities will be provided.

Introduction

Everything I say today is not official World Bank policy. I've been at the Bank for the last two years, advising about seven or eight projects on climate change and at different scales. So I'm going to try to give you an overview of that, and as we can say, anything that leans towards negative, it's just because large bureaucracies and institutions are like that, and we can talk about any organization.

The motivation for the Bank, and to understand the Bank, like many of the U.S. agencies, there are regions in the Bank. Latin and Central America, Sub-Sahara and Africa, North Africa, and the Middle East, Southern Asia, and Asia in the Pacific, and then Eastern Europe and Central Asia all work independently.

But then there is always the overarching headquarters or what's called the Anchor. So while you have activities in each of the regions, those are also replicated in the Anchor.

So there is -- as we look at it, the Anchor started an activity to try to bring a coordination of looking at climate change in the Bank, and this thought process of bringing a lot of people together. So I'm going to talk about a little bit of that, and then talk about the realities going on in the Bank.

So the Bank saw as motivation that climate change is real. That's their view at the Bank, and the world development report, which they put out, is about climate change, this year, the 10th edition. If you go on the website, you can get that, and they feel that the water sector is the most impacted.

Now, again, in the Bank, they are compartmentalized. Water in irrigation is not in the water sector. It's in the ag sector. And flooding is in roads and infrastructure. And drainage is in the transport and infrastructure sector, not the water sector. So you know, it just mirrors a lot of what goes on here in the U.S.

Now, exactly what happens is the Bank doesn't do anything. The Bank is a bank. And what happens is the technical expertise in the Bank is advising governments on strategies, but also, if a loan goes forward, then there is due diligence. For the Gibe 3 reservoir being built in Ethiopia, part of the thing is to review the plan that was done by an Italian engineering firm and due diligence on that, whether that funding they're going to loan to Ethiopia is appropriate for the dam. So that's where they get involved in that.

And finally, what came is that they feel that there's guidance needed in incorporating hydrological variability and change in our methods. So how do you guide without being proscriptive and telling people what to do, and that's been the difficult part.

So they see accelerating and broadening investments in water, and as investments in water are going up to meet millennium goals and other things, all of us in this room know that water is the most important aspect in sustainable development, and the Bank kind of feels that as well, although the roads people don't agree.

But what they're doing now in their work is to focus on adaptation and then also get involved in mitigation, and if we can build a hydropower plant rather than develop a coal-fired plant, there are funds out there to encourage that, so that's one of the things that I think is going on, as well as how can we, or should we, as an organization right now, adapt our water projects?

They've been trying to develop a method of series of adaptations and feel very much what we just heard earlier in the summary, those same kinds of topics and pushing a lot for nonstructural adaptation, if we can do them now. And then in all of this, the word that's going to keep coming forward is risk, risk, and risk.

And one of the things that's being pushed by the Anchor, and particularly through the work of Fajita Aviad, is that we need to do better decision-making of the risks. And one of the problems in the Bank and the problem is that they're not even doing what we should be doing for stationary climate in main areas, and they're not taking into account probabilistic forecasts, they're not doing Monte Carlo simulations. They're being very deterministic.

And one of the reasons for that is most of the Bank people in charge of these things are economists or policy-oriented people that -- there's not a lot of engineers reviewing what the work is, and they're always under a lot of deadlines. So to tell them to go back and do a thousand runs to get another distribution, it's just not there. So they're trying to anticipate that, and just make better development planning in that.

The other sense of that is what the anchor has been saying is we should deal with risk anyways as engineers. Let's just continue and put climate as an additional risk. That's one of the features.

So the question that they have is, the delivering of services and managing the water resources, and that the big focus that's come out of this is seeing the variability. And we've just seen that now, is that SEMA report on hydropower from the energy sector that says, there will be a constant hydropower generation of 87 kilowatt -- thousand kilowatt-hours per year from this reservoir for the next 50 years, and planning on that. Trying to understand the variability in the system that they're facing and the delivery of that.

And then what are the potential adaptations, and how can the Bank assist the client countries in making informed decisions. So in the process of developing those guidance documents, the anchor has developed the guidance document on how to deal with climate change and has done a number of short courses, trying to inform their clientele -- and some in the room have been part of that last year. They have something called the hydrologic expert facility -- in bringing in people to educate them on the issue.

Now, if we go and look at how the Bank uses GCMs, they use them every which way, wrong and right. And so there is no standard across the regions, and there's some discussions about that, but trying to tell people what is to come is pretty hard. And they will, from having Ron Webley downscale results for analysis in Morocco, to having a group that insists that all GCMs must be filtered at nine grid cells because there's too much noise in a single grid cell number. And literally, you have fights about that.

And the other thing is, there's no vetting of the data, so someone who's building a climate portal to put out climate data may actually put their biases and their things onto the work.

There tends to be consistency within regions, and that's generally because the regions tend to have one or two experts that they use for a while and their world view comes through on that. And while the Bank has been -- the water bank in Africa has been looking at what we call the extreme scenarios. What they've been trying to do is looking at the precautionary principle in doing a rapid assessment. How does it pass under the extremes of the GCM that we might see there?

It's almost a triage. If we see that it's at either of those extremes, we might not be able to handle, then they will go ahead and use that. Some groups have used the multimodel mean. The problem for Africa is in most of Africa, if you do the multimodel mean, there's no change in precipitation. So you can't go to the multimodel mean in those areas, so it brings up a lot of issues.

And one of the things that was done for a large study in Africa, an Anchor study I was involved with, was to use something which was to try to explain the GCMs using a climate moisture index. And it's really important to realize that increases in precipitation are overtaken by increases in PET with the temperature. So many of the GCMs that may have more precipitation are actually drier than other ones, so it's the joint PET and precipitation.

So using the climate moisture index, which is a ratio of annual PET, one of the things that's interesting from little graph here is that -- you shut off the whole thing here. Okay. There we go. That button turns it off. So to just notice, if you look at the globe, this is over all the land cells of the globe, what the -- the red lines in these three boxes for A2, the dashed lines are the median over the globe of your climate moisture index.

And one of the things we notice is we tend to be on the dry side globally, but the World Bank regions are much drier than the non-World Bank regions. The middle ones are the World Bank regions; the others are the non-Bank. So that's why in some levels, there's a development issue. Again, the climate impact. Look at the ranges. The ranges are also greater in the Bank regions versus the non-Bank regions.

So all the things we're dealing with here are even accentuated in the developing world, in the very dry regions that we're dealing with, and also, you have to be really careful how you use GCMs. If you use the famous ratio of the precips from the future against the past, if you have a region of Sudan where there's 10 millimeters of rainfall and there's 300 kilometers in Ethiopia with 1,000 millimeters, and the GCM grid cell says you're doubling, you have some really big problems there. So they're looking at that.

And this is -- the other thing, this is how the globe is wet and dry -- yellow is dry and blue is wet -- for each of the regions. If you take something from the globe, they vary all over the place for each of the regions. So saying a GCM is wet or dry for the globe does not match the other work.

This is an example of one of the projects that the Bank did, is they looked at the exposure in the regions of all of their investments now, and what we see is that the red is exposure of high probability of having some risk of climate change impact on the management, and their water projects in general are at risk. So that's how they view it.

What have they learned? Well, all of the things we summarized already-- they're waiting for science advances. They really understand the limits of the GCMs and how we can use them. On the other side, they're saying, pushing models beyond their intended limits is dangerous and can lead to actions that are precisely wrong.

And so the approach is really looking towards uncertainty in this and trying to look at that, and again, some of the issues that they're dealing with, which is really quite hard, is they're building a lot of dams. And one of the big issues is how do you change or recommend changes for the 1,000 year spillway design with the data that we have?

And at a meeting recently, Juan Valdez gave a nice presentation on the uncertainty bounds in our current flood frequencies. And the uncertainty on a thousand-year flood is much greater than any other things we're getting out of the GCMs. So we're adding a little bit to it, and sometimes we're actually in the Bank dealing with something that I call climate craziness.

There is so much money for climate change. It is ridiculous. And it's just -- Mozambique has just been given $100 million to look at adaptation in the next evolving strategy.

But short-term things, don't worry about it. Long-life structures, like reservoirs, large irrigation, large floodplain, start looking at climate change and see how you can hedge against it or press back kind of -- in doing some things like making the reservoir designed with a dam design such that you can add to it later. Low-carbon adaptations. Setting aside land so we can increase the floodplain later, if that's what happens. They're looking at that in the long term, and in the short term, trying to not get over-reactive to it and dealing with that.

The last thing is, one of the things we noticed is that, in the water sector, if you just look at water impacts, they're important. But the impact of water to infrastructure to transport and other things makes climate change very, very important in the large-scale development in those areas.

So they are linking this work with the disaster risk. That's a really big link at the Bank now, this disaster risk management and climate change and bringing those together, because they see it's the tails, and the things we know the least about now from our GCMs, that's scaring them.

But their action -- and this is the latest word from there -- is we need to act now, act together, and act differently. So that's the mantra of the Bank on climate change. Thank you.

NOTE: *This is a transcript of the author's remarks at the workshop that has not been reviewed or edited by the author.*

Biography

Kenneth Strzepek is a Visiting Professor at MIT's Joint Program on Science and Policy of Global Change and Professor of Civil, Environmental and Architectural Engineering, Visiting Professor of Economics at the University of Colorado at Boulder. as well as an International Fellow at the Center for Environmental Economics and Policy for Africa and Examiner in the Department of Agricultural Economics at the University of Pretoria, South Africa.

Prof. Strzepek has a Ph.D. in Water Resources Systems Analysis from MIT, an MA in Economics from the University of Colorado and is currently a Ph.D. candidate in the Department of Economics at the University of Hamburg, Germany.

Professor Strzepek has spent 30 years as a researcher and practitioner at the nexus of engineering, environmental and economics systems. His work includes applications of operations research, engineering economics, micro-economics and environmental economics to a broad range applications: from project scale to national and global investment policy studies. He has worked for a range of national governments as well as the United Nations, the World Bank, the USAID. He has been an contributing author to the Second IPCC Assessment, the Millennium Ecosystem Assessment, the World Water Vision, and the UN World Water Development Report. He is currently the USAID Scientific Liaison Office on Water and Climate Change to the CGIAR.

He is currently the Arthur Maass-Gilbert White Fellow at the Institute for Water Resources of the US Army Corps of Engineer and received the Department of Interior Citizen's Award for Innovation in the applications of Systems Analysis to Water Management, is a co-recipient of the Zayed International Prize for the Environment and as a lead author for IPCC he is a co-recipient of the 2007 Noble Peace Prize.

Water and Climate Change

A WORLD BANK PERSPECTIVE

Workshop on Nonstationarity, Hydrologic Frequency Analysis, and Water Management
15 January 2010

1

Motivation

- Sufficient evidence that cc is real
- A priority for the Bank (DCCSF) and the sector
- Climate change is more than an unprecedented environmental challenge. It is a massive development, economic and social challenge
- Water sector is among most affected
- Implications for Bank clients and investments can be serious
- Guidance is needed for incorporating increased hydrologic variability and change in investments

2

Water sector … consistent with Development and CC Strategic Framework

- Accelerate and broaden current investments in water resources management and development
- Focus on adaptation … and mitigation where relevant
  - Example: renewable resources -- Hydropower
- Develop a menu of adaptation options for water systems
  - Policies, Institutions
  - Technology
  - Infrastructure
  - Risk : Instruments for spreading and sharing
- Enable better decision-making under risk and uncertainty
  - Water services delivery and resource management
  - Assessing impacts, vulnerability, and adaptation options

3

Questions to address

- What are the impacts of climate variability and change on water systems?
  - Delivery of services
  - Management of the resource
- What are potential adaptation options to reduce vulnerability of water systems to these impacts?
- How can the Bank assist client countries in making informed decisions regarding adaptation options in their water investments?

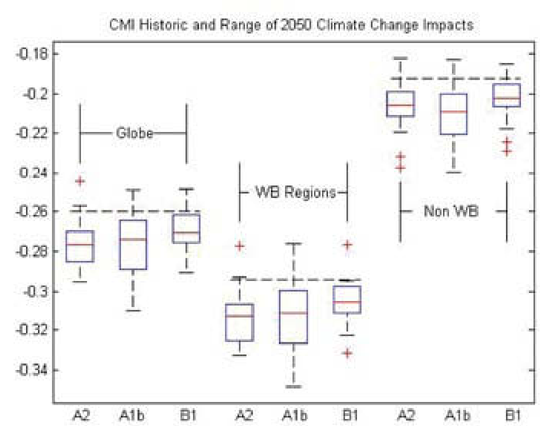
4

GCMs and WB

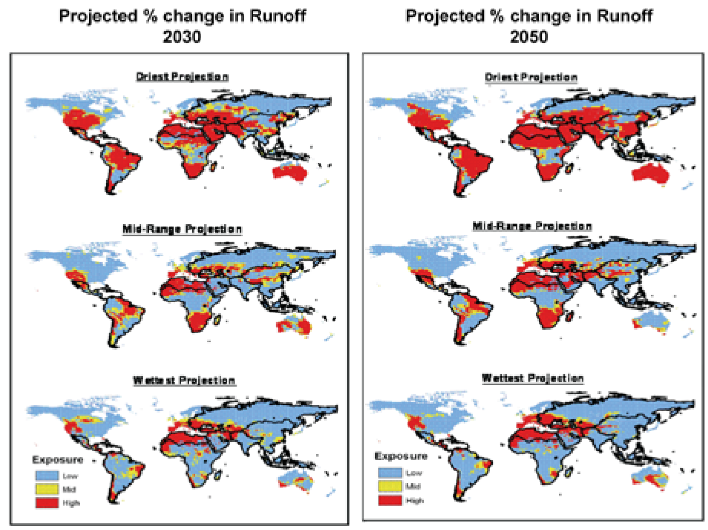
- No Standard
- From Downscaling to 9 grid filtering
- There tends to be consistency within Regions
- Some Water Anchor and Africa have been looking at the
- Extreme scenarios of Wet and Dry as defined by Climate Moisture Index
- Some use Multi-model mean

5

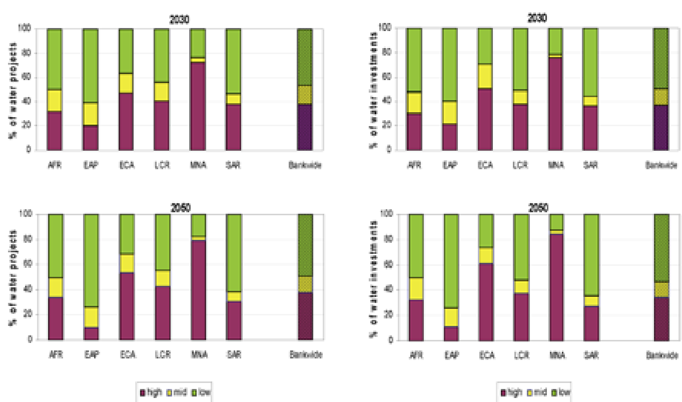
CMI



GLOBE v. REGIONS



Exposure to % change in runoff …. only by region



9

What we have learned so far …

- Climate change is only one of many factors. Future pattern of water availability/use will depend significantly on non-climate factors.
- GCMs can project general trends (T, P, extreme events) with some degree of confidence. Downscaling to high enough resolution for use in project preparation (analysis and design) can be done with relatively little confidence.
- Translating trends into runoff is not a straight-forward exercise, as many claim.
- Consequently, there is significant uncertainty in changes in the hydrologic drivers.
  - The past cannot be used as the only guide for the future. Hydrologic non-stationarity

10

What we have learned so far …

- We know much less than we should, but must make investment and financing decisions none-the-less.
- Waiting until science advances far enough is not an option.
- Pushing models beyond their intended limits is dangerous and can lead to actions that are "precisely wrong".
- Uncertainty is a given in the sector. We just have to deal with it better.
- The decision process in dealing with risk and uncertainty is essentially the same with and without climate change.
- Bottom-up and Top-Down approaches are complimentary.
  - Top down approach (projections to vulnerability to adaptation) is not in all cases useful for decision making in operations.
  - Bottom up approach (vulnerabilities of water systems: reliability, resilience, robustness) is far more useful in most cases.

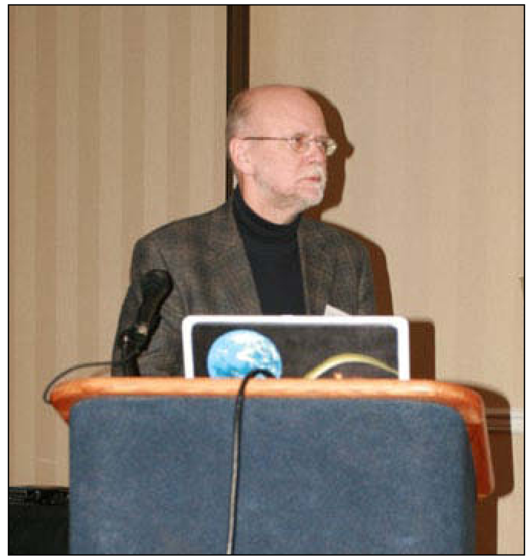
11

Nonstationarity in Water Resources: Central European Perspective

Zbigniew W. Kundzewicz, Institute for Agricultural and Forest Environment, Polish Academy of Sciences, Postdam Institute for Climate Impact Research

Nothing is permanent but change - Heraclitus

There is nothing in this world constant but inconstancy - Jonathan Swift



Abstract

Nonstationarity in variables describing water quantity and water quality characteristics is reviewed and attempt to interpret nonstationary behaviour is made with particular reference to Central European region. Nonstationarity in water-related variables results from several non-climatic and climatic factors. Albeit evidence of climate change in Central Europe is clear, anthropogenic non-climatic change, such as land-use or land-cover changes, water engineering measures, and in-catchment water management play important roles. Systemic socio-economic and political changes are the main factors responsible for the observed change in water quality in the region. The observed climate change in the Central European region has not been dramatic enough to persuade the water management community that changes of standards, criteria, and evaluation procedures should be made. Projections for the future largely differ between models and scenarios, hence information obtained from climate models is found too vague to be used. However, water management community shows interest in climate change observations, projections, and impact assessments. Numerous hydrological research projects to tackle nonstationarity have been undertaken in the region. Also important acts of legislation, such as European Union's Water Framework Directive and Floods Directive can be regarded in the context of nonstationarity of water-related variables.

Notions of Nonstationarity

The scientific term "stationarity" does not necessarily mean constancy of variables. What it does mean is constancy of laws and patterns. Hence, generalization of the mottos from Heraclitus and Jonathan Swift can embrace stationarity. Variables may feature strong, but regular, natural variability and quasi-periodic oscillations, while the processes ruling the changes can be nearly constant.

A stationary process, per definition, has a property that its probability distribution does not change with time. That is, if parameters such as mean and variance exist, they are constant. In contrast, statistical properties of nonstationary processes vary over time, e.g. featuring abrupt or gradual changes in the mean, variance, higher moments, or characteristics of extremes.

Nonstationarity opens a Pandora's box with problems. Constancy of statistical properties allowed water planners to coin a convenient notion of a 100-year flood or a 100-year streamflow drought (i.e. a river discharge, whose probability of exceedance in any given year is 0.01 or 0.99, respectively). In nonstationary situation the notion of 100-year event has to be re-defined. Also, the definition of the power spectrum is not straightforward, as variation in properties can be interpreted as low frequency noise.

There exist several interpretations of the term "stationarity", hence the paper by Milly et al. (2008), declaring that "stationarity is dead" raised controversy. According to some experts, there has never been stationarity in water resources and there

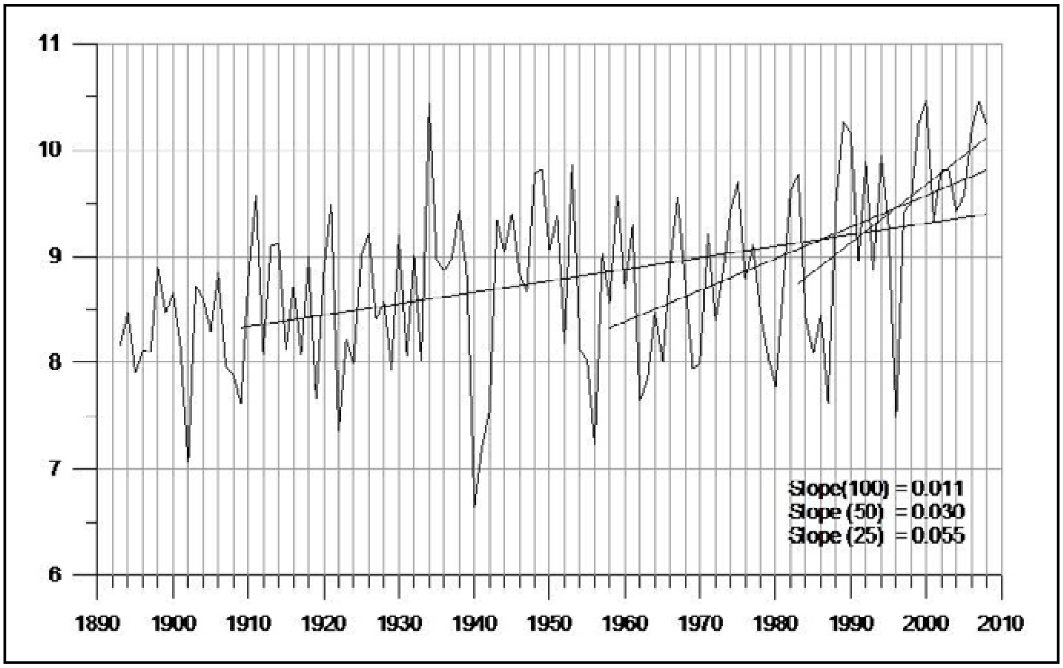


Figure 1. Changes in mean annual temperature in Potsdam.

exist many reasons for nonstationarity. Stationarity can be interpreted as the rule "the past is a key to the future". Literally – a key should open the door. If it does not, it can mean either that the key is worn out or that the lock has changed. However, even if in nonstationary systems the past is not a key to the future (it does not really open the door), there are useful lessons that can be learnt from the past.

If an extreme event occurs, that is more extreme than all events ever observed, this does not necessarily mean that the process is nonstationary. With increasing length of time series of records, one may expect more extreme extremes to occur, also under stationarity reign. With longer data sets one gets a decreasing sampling error.

With modest observation record we do not know where we are even in stationary situation. A rigorous statistician would demand at least 100 years of data, in order to reliably estimate a 20 year-flood, under stationarity. In fact, often we have only 20 years of observation data and have a task to estimate a 100-year-flood, in a clearly nonstationary situation.

Meteorological and climatical variables	Total precipitation; intense precipitation; snow cover, snowmelt; seasonal distribution of climatic variables, and climate variability (e. g., ENSO)
Hydrological variables	River discharge and stage (amplitude, frequency statistics, seasonality); water storage capacity (e. g., flood plains and wetlands); runoff coefficient and infiltration capacity, water storage capacity, or rate of impervious area
Anthropogenic pressure	Population growth, urbanization, deforestation, channelization, and human occupation of non-safe areas (especially squatter settlements)
Flood damage measures	Number of fatalities; number of evacuees; total material damage; insured losses; losses in cultural heritage; further specification of losses (e. g., destroyed infrastructure, buildings, industrial plants, railways, bridges, roads, dikes); inundated area (therein agricultural land); health damage; loss to animal husbandry; wildlife damage; indirect damage (e.g. lost benefits, crop loss); Social characteristics Risk perception; adaptive capacity; vulnerability
Social characteristics	Risk perception; adaptive capacity; vulnerability

Table 1. A sample of flood-related variables.

Problems with water can be divided, generally, into three categories - having too much water, too little water and water in inadequate quality. These problems can be conveniently tackled with the help of a load-resistance analogy. Nonstationarity means that statistical properties of both load and resistance variables may change in time. Table 1 illustrates a sample of flood-related variables, where loads can be interpreted as river discharge and stage (resulting from precipitation or snowmelt), or anthropogenic pressure, while resistance can be interpreted as the threshold of discharge or stage where damage starts.

Nonstationary behaviour can be traced in several flood-related variables (cf. Kundzewicz & Schellnhuber, 2004), such as those listed in Table 1.

All three basic categories of water-related problems listed above have manifested themselves in the Central European region. The abundance of water, leading to destructive floods occurs in the region from time to time (most recent major flood events occurred in 1997 and 2002). Having too little water occurs more frequently (summer droughts every few years), while water pollution, the heritage of decades of inadequate wastewater management has been ubiquitous and has manifested itself in the inadequate water quality in most rivers and water bodies (Kundzewicz, 2001).

This contribution presents a Central European perspective on nonstationarity of water resources, including, but not limited to, climate change.

Observed Changes

In the global super-system, everything is connected to everything else, so that any change in any component system may induce changes in many other, interlinked, systems.

Clear violation of stationarity in water resources results from human activities. Many river basins experience massive manipulations of the land and water resources (e.g. in support of humans to provide shelter, food, fibre, fodder and fuel). Human activities in river basins are driven by population changes and by economic development. A saying goes that there is no such thing as a free lunch – apart from targetted benefits, there are adverse side effects of any human activity involving land and water resources manipulations.

Development at the river basin scale usually means a roster of anthropogenic changes, such as:

- Changes in land-use practices, like urbanisation, intensification or extensification of agriculture, deforestation or aforestation, mining, resulting in land-cover change;
- Water engineering measures in rivers, e.g. levee and dam construction, straightening and shortening of rivers, in-channel modifications (dredging, channelisation); or
- In-catchment water management, like water abstractions, irrigation, water transfer schemes, wetland drainage.

Time interval between action and impact can be significant and some land-use change impacts may become obvious only after a considerable time lag. For example, the effects of afforestation on low flow, or nitrate pollution of groundwater may be revealed only decades later.

The rise in exposure to floods has been caused by human encroachment into floodplains. It may grow as people become wealthier and more exposed. Technology and economic imperative help populate more “difficult” areas. Many wrong locational decisions have been taken, and the assets at risk from flooding are enormous, and growing.

There have been considerable nonclimatic changes in Central Europe, influencing water resources, such as changes in the number of inhabitants (slight decrease), land-use changes (urbanization and afforestation), and economic growth. Systemic change observed in the last two decades is of huge importance for many water-related parameters, in particular – characteristics of water quality.

Since 1989, the region has witnessed significant socio-economic and political changes – from single-party communism and centrally-planned economy to democracy, capitalism and market economy. During the transition period following the system change, the industry and agriculture were largely overhauled. The outdated, ineffective, and polluting industries, which used much energy and raw materials (including water) and the collective (and previously - highly subsidized) agriculture have largely collapsed, leaving high acreage of abandoned land. This has considerably influenced water availability and demand and water quality in the region (Krysanova et al., 2006). Transformation of agriculture resulted in reduction of the use of agrochemicals, which became more expensive, virtually unaffordable to many farmers. Drop in concentration of animal production (by liquidation of large state-owned units) reduced environmental threat related to local overloads of manure. On the other hand, there has also been some progress in agricultural practices (new cultivars, improved tillage, optimizing rates and timing of fertilizers' application). There exists advanced environmental legislation in the European Union (EU), including the Water Framework Directive (effective since 2000), which requires that by the year 2015, all waters in the EU should be of good quality.

Reducing inflow of pollutants by way of construction of further wastewater treatment plants is indeed an appropriate step towards improving water quality. The volume of sewage in the need of treatment, that were fed untreated to waters, has been monotonously decreasing. In Poland, in 1998 its volume dropped to below 500 hm3/year (a quarter of the 1980-1985 level) and in 2002 – to one tenth of the 1980-1985 level. This is still not enough to comply with the EU legislation, but the dynamics augurs well (Krysanova et al., 2006).

There has been an increasing body of evidence of the ongoing warming of the atmosphere at a variety of scales, including the global scale, with mean global surface temperature increasing by 0.65°C over the last 50 years (IPCC, 2007). However, the peculiarity (out-of-normal?) of this global temperature trend is also being questioned. Cohn and Lins (2005) found that it is Nature's style to be naturally trendy. By playing with model assumptions they lose 25 orders of magnitude and prove the trend insignificant.

Precipitation changes are less regular, but increases over land north of 30°N over the period 1901–2005 were observed (Trenberth et al. 2007). Several studies lead to the conclusion that, over the last 50 years, there has been an increasing probability of heavy precipitation events for most extra-tropical regions; at the continental and global scales (cf. Groisman et al. 2005; Trenberth et al. 2007). It is likely that there have been widespread increases in the number of heavy precipitation events (e.g. 95th percentile) and in the contribution to total annual precipitation from very wet days, i.e. days in which precipitation amounts exceed the 95th percentile value, in many land regions. However, the rainfall statistics are strongly influenced by inter-annual and inter-decadal variability. There are problems with data homogeneity, e. g. related to changes in snowfall.

Observed changes of the timing, intensity, duration and phase of precipitation in a site of interest, or in a region, are often weak and statistically insignificant. But even if significant changes are detected, they can be inconsistent throughout regions and seasons.

The sea level has been rising over many last decades, with considerable impact on freshwater (e.g., saltwater intrusion into groundwater and estuaries). The principal mechanisms of the level rise have been: thermal expansion resulting from temperature rise and melting of the cryosphere (including mountain glaciers, that are a source of water supply to more than a billion people). The global average rate of recent sea level rise, measured by satellites from 1993 to 2003 is 3.1 ± 0.7 mm/year^{-1} (IPCC, 2007). In the estimated total, thermal expansion is responsible for 1.6 ± 0.5 mm/year^{-1} and cryospheric changes – for 1.2 ± 0.4 mm year^{-1}, but the sea level budget still does not close – observations and estimates differ by 0.3 mm/year^{-1}, even if now this difference is decreasing in time.

In Central Europe, several facets of climate change have been observed. Warming has been ubiquitous, noted everywhere, for every season, and in different aspects (mean, maximum and minimum temperatures). Figure 1, presenting the mean annual temperature at Potsdam station shows a clearly increasing tendency, much stronger than the global average. The rate of warming grows with time. The slope of the regression line for the last 25 years was nearly twice stronger than during the last 50 years and five times stronger than for the last 100 years (Kundzewicz and Huang, 2010). All these changes are statistically significant at least at 0.01 level. However, Figure 1 demonstrates that even slight shifting of the time horizons of regressions in may impact results.

In contrast to temperature change, changes in other variables of relevance to water management are not that clear. There are evident changes in seasonality of precipitation, such as well-visible decrease of the ratio of summer precipitation to winter precipitation (Pińskwar, 2009), and change of the distribution of the phase of winter precipitation (on average, more liquid and less solid precipitation). Less snow cover in Central Europe results in less abundant, and earlier, snowmelt.

Observed Changes in Hydrological and Water Resources Variables

Streamflow generation is a complex process, integrating influences of many climatic and non-climatic factors, Variations in river discharge reflect variations in meteorological conditions (precipitation, temperature), changes in land use (catchment storage, rate of impermeable area, forested, and agricultural land), and human regulations of water cycle (dike and dam building, irrigation and drainage, etc.). The effects of climate change on streamflow follow changes in precipitation

Figure 2. Four times the flood of July 1999 was the motive of a cover story and a cover photo of the influential Polish weekly magazine, Polityka [The Politics].

(volume and timing, and whether precipitation falls as snow or rain) and changes in evapotranspiration, dependent on several variables, including atmospheric CO_2 concentration, temperature, energy availability, atmospheric humidity, and wind speed. It is very difficult to disentangle the climatic effects on river flow from the effects of human interventions. A robust finding is that warming leads to changes in the seasonality of river flows where much winter precipitation falls as snow, with spring flows decreasing because of the reduced or earlier snowmelt, and winter flows increasing, with likely consequences to flood risk.

Labat et al. (2004) claimed a 4% increase in global total runoff per 1°C rise in temperature during the twentieth century, but this finding has been challenged (Legates et al., 2005) because of the effects of nonclimatic drivers on runoff and bias due to the small number of data points. Gedney et al. (2006) attributed the observed rise in global river runoff primarily to plant physiology effects (CO_2-fertilization inducing increased efficiency of water management of a single plant, and reduction in plant evapotranspiration) offset by climate change (precipitation, temperature) signal, however, this attribution is uncertain. Significant trends in some regional indicators of river flow have been identified in some studies (e.g. a broadly coherent pattern of change in annual river runoff, in Milly et al., 2005), but no globally homogeneous trend has been reported. In some regions, interannual variability of river flows is strongly influenced by large-scale systems of ocean-atmosphere variability associated with El Niño-Southern Oscillation (ENSO), North Atlantic Oscillation (NAO) that operate at time scales of years and decades.

Detection of climate change in river flow data is inherently difficult, because of the low signal-to-noise ratio. The relatively weak climate change signal is superimposed on a large natural, inter-annual variability of rainfall and river flow (under a confounding effect of land-use change). I subscribe to the opinion by Wilby et al. (2008), who stated that, in some areas, statistically significant trends are unlikely to be found for several decades more.

Characteristics of water-related extremes – droughts, intense precipitation, and floods – have changed during the twentieth century. Destructive floods observed all over the world in the last decades have led to record high material damage. The costs of extreme weather events have exhibited a rapid upward trend, and yearly economic losses from large events have increased by order of magnitude between the 1950s and 1990s in inflation-adjusted dollars (IPCC, 2001). Disaster losses have grown more rapidly than population or economic growth, suggesting a climate change element (Mills, 2005).

There is abundant evidence for an earlier occurrence of spring peak river flows, and an increase in winter base flow in basins with important seasonal snow cover in Central Europe. This is in agreement with regional climate warming. The early spring shift in runoff leads to a shift in peak river runoff away from summer, which is normally the season with the highest water demand.

From time to time, destructive flood disasters visit the Central European region. There was an extreme flood in July 1997, devastating large areas in the Czech Republic, Poland, and Germany. The record discharge observed in Raciborz-Miedonia on the Odra in Poland was more than twice higher than the former record. Some say that the world is no worse off than

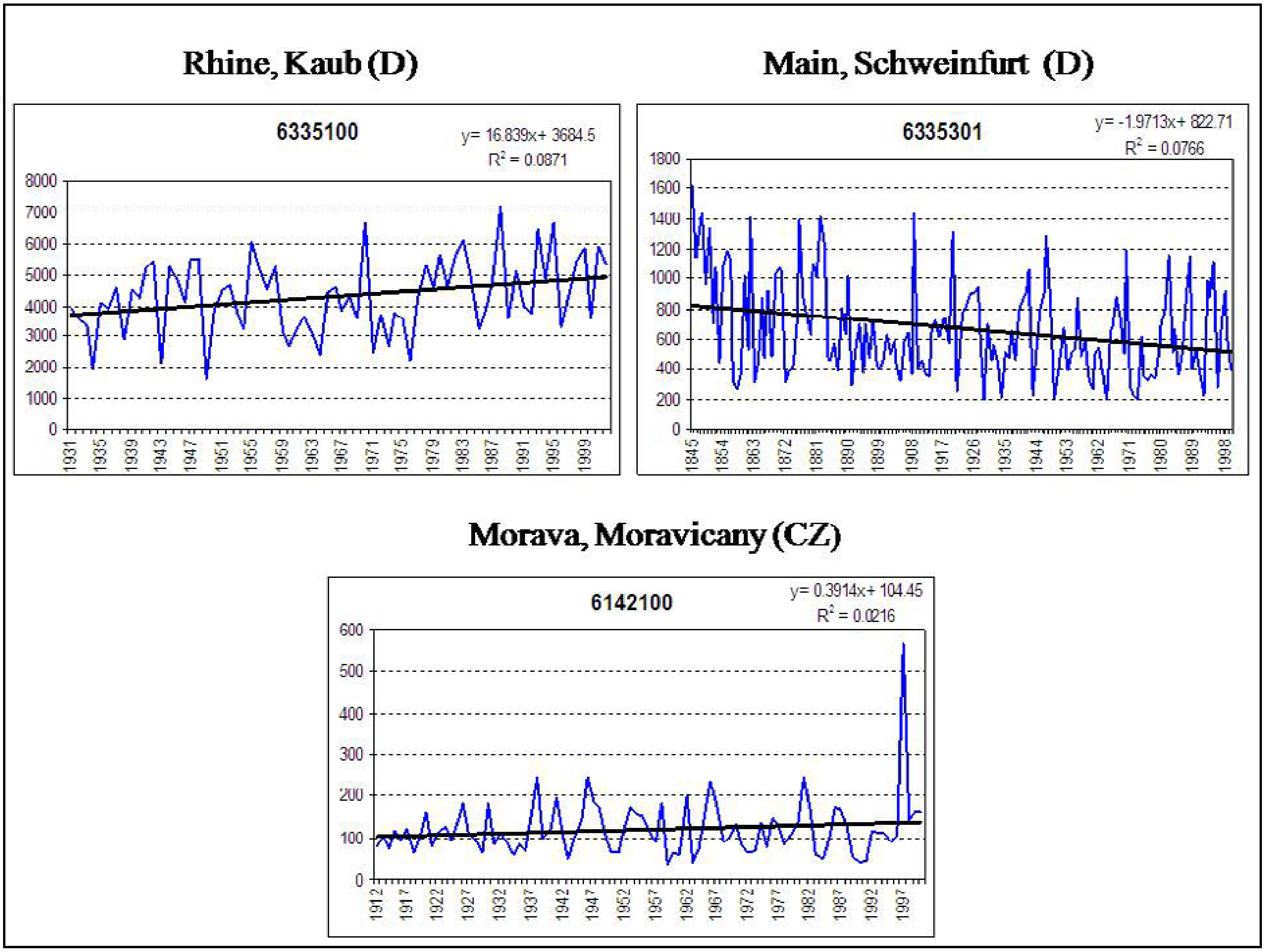


Figure 3. Examples of time series of annual maximum discharge of European rivers.

a few decades ago, and it is just that the news coverage is much better (a CNN effect) and focussed on the negative side of things. This statement can be illustrated by an unprecedentent, spectacular, flood of July 1997 in Poland. To the knowledge of the author, it is unprecedented worldwide that for four weeks, the flood was the theme of the cover story and of the cover photo of the most influential and opinion-making national weekly magazine (Figure 2). Flood management was rated inadequate by the Polish nation and in result the national government fell (cf. Kundzewicz et al., 1999).

Another recent example of extreme event in Central Europe was the flood in August 2002. This was the year with ever highest flood damage in Europe, exceeding 20 bilion Euro. The international River Elbe (Labe), flowing through Czech Republic and Germany, inundated Dresden, the capital city of Saxony, where the observed water stage was highest on record (940 cm on 17 August 2002). However, this record does not look like a part of an increasing trend, in the context of data from the past. During the whole 20th century, the maximum water level of the Elbe in Dresden was only 674 cm, i.e. 366 cm less than the 2002 peak. Hovewer, there were 10 exceedences of the level of 800 cm since the Middle Ages. Between 1600 and 1880, most large floods were caused by snowmelt and ice jams and occurred in February or March. The all-time record, in August 2002, was caused by a very heavy, long-lasting, and large-area covering rainfall. Dramatic flooding occurred also in the Czech Republic, e.g. on the River Vltava, that inundated Prague, the capital city. In August 2002, the ever highest discharge of the Vltava in Prague was reached, in excess of 5000 m^3/s. Again, also this record cannot be seen as a manifestation of a smooth increasing trend. During the 20th century the discharge of 4000 m^3/s was never reached. Nevertheless, it was exceeded three times in the 19th century.

Despite these all-time record events in Central Europe, to-date observations provide no conclusive and general proof as to how climate change affects flood behavior. One can note different, river- and interval-specific behaviours of annual maximum river discharge data in Central Europe (Figure 3) - increasing trends, decreasing trends, no change; but even if a change is detected, usually it is not statistically significant (Kundzewicz et al., 2005, Svensson et al., 2005). Kundzewicz et al. (2005) examined 70 time series for river discharge in Europe over the 40 year interval, 1961–2000. They found that the overall maxima occurred more frequently (46 times) in the second 20-year sub-period, 1981–2000, than in the first 20-year sub-period, 1961–1980 (24 times). Among observed climate-related phenomena impacting on floods in Europe are increase in precipitation intensity; increase in westerly weather patterns during winter; and shrinking snow cover. A regional change in timing and nature of floods has been observed in many areas of Europe, and less snowmelt and ice-jam-related floods were recorded. Mudelsee et al. (2003) demonstrated a significant decrease in winter floods at the Elbe and the Odra/Oder.

In the past three decades, droughts have become more widespread, more intense and longer, globally, due to decreased land precipitation and warming that enhanced evapotranspiration and drying. Dai et al. (2004) showed that very dry areas (defined as land areas with the value of Palmer Drought Severity Index, PDSI ≤ -3.0) more than doubled globally from ~12 to 30% since the 1970s, while Groisman et al. (2007) found increased dryness in northern Eurasia. However, results of a search for trends in hydrological drought for over 600 streamflow records in Europe, carried out by Hisdal et al. (2001), did not support the general hypothesis of increasing severity or frequency of drought conditions. Also Svensson et al. (2005) did not detect overwhelming decrease in low flows.

The most unabated change of climatic variables driving water quality is the ubiquitous air temperature growth, observed at all spatial scales. Stream water quality is clearly influenced by the resultant growth of water temperature that drives the reaction kinetics of key chemical processes. Warming accelerates nutrients' cycling. Moreover, increasing water temperature leads to a decrease of oxygen carrying capacity and hence drop of dissolved oxygen concentration, adversely affecting the self-purification capacity of streams.

Water-related extremes, floods and droughts, become more frequent and more severe in the warming climate, and this largely influences water quality. Increase in intense precipitation affects the rate at which pollutants are flushed to rivers. During floods, overloaded storm sewer systems and wastewater systems may become sources of water pollution. Water quality problems during droughts can be severe as well, since decrease in flow volumes adversely affects dilution of nutrient and pollutant loads. A saying goes that "dilution is not a solution to pollution", yet, in fact, dilution is very important – if streamflow is low and the amount of sewage influx remains in the same range, the stream water quality suffers.

On the top of climate change impacts, there are substantial non-climatic factors affecting stream water quality. In fact, over some areas, such as Central Europe, impacts of non-climatic factors on water quality largely exceed the impacts of climate-related factors. Among the non-climatic factors of importance to stream water quality are changes in pollutant emissions, echoing developments in wastewater treatment; land-use changes (e.g. changes in agriculture extent and practices, such as fertilization and irrigation; urbanization), environmental regulations, and changes in environmental awareness.

A decrease in overall water demand has been noted in Central Europe. Total withdrawals, withdrawals for production targets, irrigation in agriculture and forestry, and municipal water supply have decreased and efficiency of water use has improved. Water demand was found to be strongly influenced by economic instruments and in particular – water pricing. Before the system change, consumption of underpriced water was high. In result of collapse of much of production, and growth of water prices, water consumption considerably decreased in countries of Central Europe (Kundzewicz, 2001). However, with economic recovery and growth, water demand increases.

Projected Changes

Model-based temperature projections agree on the sign of change – ubiquitous warming is projected (cf. Solomon et al., 2007). Climate projections show also increases in globally averaged mean water vapor and precipitation over the 21st century. However, in contrast to straightforward temperature changes, observed model-based projections of future precipitation are considerably less clear and much more uncertain. There is a strong inter-model uncertainty – over large areas, climate models disagree even as to the direction of change of future precipitation, spanning a broad uncertainty range.

Precipitation scenarios show strong regional differences. In Europe, there is a marked contrast between projected winter and summer precipitation change. Wetter winters are expected throughout the continent (in many places – less snow and more rain), while in summer, precipitation in northern Europe is projected to grow (wet getting wetter) and in southern Europe to decrease (dry getting drier), cf. Kundzewicz et al. (2006).

Generally, precipitation extremes are likely to be impacted more than the means. The highest quartiles of daily precipitation amounts and annual maximum daily precipitation are anticipated to increase over much of Europe. Yet, existing climate models are not good at reproducing local climate extremes, due to, inter alia, inadequate (coarse) resolution. Hence, projections of extreme events for future climate are highly uncertain.

There are many sources of uncertainty in projections. Uncertainties are associated with emissions, climatic drivers (e.g. the carbon cycle), climate (e.g. climate model sensitivity and pattern of climate change), and impacts (including adaptation). The initial uncertainty, relating to future human development, is considerably amplified along this chain; for the same emission scenario, different models give rise to different impacts. This difference is often larger than that arising in one model with different emission scenarios. For example, for precipitation changes until the end of the 21st century, the multi-model ensemble mean exceeds the inter-model standard deviation only at high latitudes (Kundzewicz et al., 2007). Uncertainties in climate change projections increase with the length of the time horizon. In the near term, climate model uncertainties may play a more important role; while over longer time horizons, uncertainties due to the selection of emissions scenario become increasingly significant.

By mid-century, annual average river runoff and water availability are projected to decrease by 10-30% over some dry regions at mid-latitudes and in the dry tropics, while increasing by 10-40% at high latitudes and in some wet tropical areas (Milly et al., 2005), and more pronounced changes are likely to occur by the end of this century (Kundzewicz et al., 2007). Most models project decrease in annual average river runoff over Central Europe.

Palmer and Räisänen (2002) projected a considerable increase in the risk of a very wet winter in Europe. For example, for CO_2 doubling, a five-fold increase of the risk of a very wet winter is projected over much of the Baltic Sea basin, and even seven-fold increase for parts of Russia.

Based on results of Hirabayashi et al. (2008) and Dankers and Feyen (2008) one can compare (Kundzewicz et al., 2010) projections of flood hazard. For much of Europe, what used to be a flood with exceedance probability of 1 in 100 years (so called 100-year flood) in the control period becomes either more frequent or less frequent in the future time horizon of concern. According to results by Hirabayashi et al. (2008) and Dankers and Feyen (2008), over 40% of the area of Europe the control 100-year flood is projected to become more frequent, while over 30% of the area of Europe, the mean recurrence interval of the 100-year flood in the control period is projected to decrease to below 50 years in 2071-2100.

Dankers and Feyen (2008) project that on several major rivers in Central Europe, such as the Odra (Oder), Labe (Elbe), and parts of the Danube, large floods will become more frequent by the end of the 21st century. In these rivers, the average return period of a 100-year flood reduces to once every 20-50 years, on average. However, in several rivers in Central and Eastern Europe, probability of exceedence of a control design flood decreases.

Comparing Hirabayashi et al. (2008) and Dankers and Feyen (2008), one can find areas, where results are consistent, e.g. today's 100-year flood projected to be exceeded less frequently in 2071-2100 over most of Finland, and European part of the Russian Federation (regions prone to snowmelt floods), while it is projected to occur more frequently in much of Poland, and Southern Sweden. One can find inconsistencies between models over much of Belarus and Lithuania.

With respect to drought, the projections for the 2090s made by Burke et al. (2006) show a net overall global drying trend. Globally by the 2090s, the land surface suffering from extreme drought is projected to increase in extent, while the proportion of the land surface in extreme drought at any one time is predicted to increase ten-fold from the present. The number of extreme drought events per 100 years and mean drought duration are likely to increase by factors of two and six, respectively, by the 2090s. The overall drying trend is projected with a decrease in global average value of the Palmer Drought Severity Index of 0.3 and 0.56 per decade, respectively, for the first and the second half of the 21st century (Burke et al., 2006).

Lehner et al. (2006) analysed projections of droughts in Europe, based on two climate models (HadCM3 and ECHAM4). What used to be a 100-year drought in the control period (1961-1990) is projected to be exceeded much more frequently in 2020s, and even more so in 2070s over much of Central Europe. Results based on the German ECHAM4 model illustrate a prospect of dramatic increase in drought risk over the territory of Poland.

Water Management under Nonstationarity

At present, uncertainty of projections is very strong, so that GCMs and downscaling are not ready for prime time yet. Downscaling cannot compensate for the basic inadequaties of the climate models. A question: "Adapt to what?" comes about.

A call to reduce uncertainties was issued in the IPCC First Assessment Report in 1990, but since then the uncertainties have grown – we know increasingly better that we know little. There are inherent, possibly irreducible, uncertainties of the climate system, so that a shift of emphasis from "reduce uncertainties" to "risk reduction" tends to be necessary. The point is – to make rational decisions without being able to know the future with adequate precision?

Detection of changes in long time series of hydrological records is an important scientific issue, fundamental for planning of future water resources and disaster protection. If studies come to predict in a reliable way a significant increase in the severity of hydrological extremes in the changing world, then the consequences for the existing procedures of designing dikes, spillways, dams and reservoirs, by-pass channels, etc., traditionally based on the assumption of stationarity of river flow, would be severe. For instance, in some areas, one would have to design and build higher levees and larger storage volumes, at higher costs, to accommodate larger future flood waves. Existing infrastructure may not guarantee the adequate level of protection and may need to be re-adjusted (Milly et al. 2008). Without this, systems will be over- or under-designed and will either not serve their purpose adequately, or will be overly costly.

Climate change and water management in Central Europe: The observed climate change in the Central European region has not been strong enough yet to persuade the water management community to change standards, criteria, and evaluation procedures. Projections of future precipitation and river discharge largely differ between models (and scenarios), hence GCM-based information is found too vague to be used. However, water management community shows interest in climate change observations, projections, and impact assessments.

Numerous hydrological research projects dedicated to detection of change in hydrological variables, projections for the future, and development of methodologies to tackle nonstationarity have been undertaken (funded nationally, or by the European Union). Moreover, Central European nations are obliged to comply with the environmental legislation of the European Union, such as the Floods Directive (CEC, 2007), where climate change is explicitly considered.

Due to the difficulty in isolating the greenhouse signal in the observation records and the large uncertainty of projections for the future, no precise quantitative information can be delivered from academia to practitioners. However, increasingly risk-averse societies of the European Union undertake simple, common-sense, efforts to increase safety margins based on climate change impact scenarios. In parts of Germany (e.g. the states of Saxony or Bavaria), flood design values have been increased, based on climate change impact scenarios. The projections in Bavaria for 2050 include an increase of 40-50 percent in small and medium flood discharges and of around 15 percent in 100-year floods. In the UK, the Defra's precautionary allowance includes projection of increase in peak rainfall intensity (up to 20% by 2085 and 30% by 2115) and in peak river flow volume (up to 10% by 2025 and 20% by 2085), cf. Defra (2006), to reflect the possible effects of climate change, based on early impact assessments. Measures to cope with the increase of the design discharge for the Rhine in the Netherlands from 15 000 to 16 000 m3/s must be implemented by 2015 and it is planned to increase the design discharge to 18 000 m3/s in the longer term due to climate change. A 'climate change factor' shall be taken into account in any new plans for flood control measures in the Netherlands (EEA 2007). One can expect that in those areas where 100-year floods become lower and the adequate, and properly maintained, protection systems are already in place, the existing defenses will provide higher-than-standard protection level.

Regional studies devoted to the impact of climate change on flood damages in Europe are scarce, but Feyen et al. (2009) arrived at averaged expected annual damages at the EU and country level. It was assumed that the flood protection level depends on the country's GDP (protection up to 100-year, 75-year, and 50-year flood for countries with GDP above 110 percent in the range from 55 to 110 percent; and below 55percent of the average GDP level in 27 EU Member States, respectively). Also a simplifying assumption of no adaptation to increasing flood levels and no growth in exposed values was made. Under these assumptions, useful and interesting indicative results were obtained, thereby the present expected annual damage was projected to nearly treble in 2071-2100. In five countries the expected annual damage in the future horizon was projected by Feyen et al. (2009) to exceed 1 billion Euro, with highest value being 4 billion Euro. Out of 25 countries with non-zero flood damages in the control period, increase (up to 80%) is projected in 20 and decrease (even by 85%) is projected in 5 countries.

In response to destructive recent floods in Europe and projections of growing flood risk, in April 2007, the Parliament and Council of the European Union passed a new important act of legislation, Directive on the assessment and management of floods, commonly known as the Floods Directive (CEC, 2007), embracing river floods, flash floods, urban floods, sewer floods and coastal floods. The objective of the Directive is to reduce and manage the risks which floods pose to human health, the environment, infrastructure and property.

The Directive, which applies to the whole European Union territory, states that EU Member States shall, for each river basin district or the portion of an international river basin district lying within their territory, undertake:

- A preliminary flood risk assessment (a map of the river basin; description of past floods; description of flooding processes and their sensitivity to change; description of development plans; assessment of the likelihood of future floods based on hydrological data, types of floods and the projected impact of climate change and land-use trends; forecast of estimated consequences of future floods);
- Preparation of flood hazard maps and flood risk maps (i.e. damage maps), for high risk areas which could be flooded with a high probability (such as 10-year flood); with a medium probability (return period of 100 years), and with a low probability (extreme events);
- Preparation and implementation of flood risk management plans, aimed at achieving the required levels of protection, by 2015.

Given the diversity across the EU, the Floods Directive (CEC, 2007) provides flexibility for Member States to determine the level of protection required, the measures to be taken to achieve this level of protection (taking into account the work already done at national and local level), and the road maps for implementing flood risk management plans.

It is expected that implementation of the Directive, probably the most advanced legislation worldwide in the area of flood protection and flood preparedness, will considerably reduce the flood risk throughout the European Union. By mandatory activities, such as assessment, mapping, and management of flood risk in the river districts, upgrading of the preparedness systems is expected, at an unprecedented multi-national scale.

In 2000, the Water Framework Directive (WFD) was adopted, regulating actions of the European Union in the field of water policy. The Directive treats the water quality problem as a complex one, and requires integrated water management in river basins based on a combined approach of water quality standards and emission limit values. This new legislation also expands the scope of water protection to all waters, surface waters and groundwater, and sets an obligation to achieve good water quality status of all waters in the European Union within a set deadline of 2015. The Directive imposes legal obligations for the authorities in all EU Member States. Implementation of the Directive (cf. Hattermann and Kundzewicz, 2010) is likely to induce beneficial effects on stream water quality in less developed areas in the EU, including Central Europe.

It is expected that implementation of the Water Framework Directive would follow success stories, such as the successful cleanup of the Rhine, once known as "Europe's sewer". Following the industrial development, water quality of the Rhine increasingly deteriorated for decades since the beginning of the 20th century. Wastewater treatment was missing completely until the first wastewater treatment plant was built in 1954. Besides, in November 1986 due to a catastrophe in the chemical factory Sandoz in Basel (Switzerland), large amounts of dangerous chemicals entered the river's water, causing death of all living organisms at the 400 km downstream section of the Rhine. However, the international cooperation, including the Program for Action – Rhine, established in 1986 led to considerable improvements. The measures used were: monitoring program, water quality indicators and target standards for quality assessment and harmonization of methods and technologies of wastewater treatment. The first priority was to cope with municipal and industrial wastewater treatment. Now, dozens of fish species live in the Rhine, including salmon and ocean trout.

Concluding Remarks

This contribution presents a Central European perspective on nonstationarity of water resources, understood as temporally-changing probability distributions of water-related variables. A review of climatic and non-climatic causes of nonstationarity is offered, with particular reference to three classes of water-related problems – having too little water, too much water, or polluted water. Even if climate change has been pronounced in the region, other, non-climatic changes were very strong, and to-date can be considered the main source of nonstationarity. Interplay of multiple factors can be illustrated at the example of river flooding, where several factors may be responsible for increase in flood damages, such as changes in socio-economic, terrestrial, and climate systems. Relevant socio-economic changes include increasing exposure and damage potential due to population growth and economic development of flood-prone areas, land-use change leading to land-cover change (e.g. urbanisation, deforestation), and changing risk perception. Changes in terrestrial systems include changes in hydrological systems and ecosystems, including land-cover change, and river regulation measures such as channel straightening and shortening, and constructing embankments. Conditions of transformation of precipitation into runoff are also subject to change, leading to reduction of storage (drainage of wetlands and elimination of natural vegetation; increase of impermeable areas), a higher flood peak, and a shorter time-to-peak. Last, but not least, changes in climate are important, even if they may not be ubiquitously detectable in the historical record yet, but may become detectable in a few decades. Relevant climatic changes include: increasing water holding capacity and water contents of the atmosphere in the warmer world, increases in frequency of heavy precipitation, and changes in seasonality and in atmospheric circulation patterns.

Acknowledgements

The author acknowledges invitation from organizers to partake in the important workshop on "Nonstationarity, Hydrologic Frequency Analysis, and Water Resources Management" in Boulder, with an oral contribution that backed the present document. The work on this document was carried out within the WATCH (Water and Global Change) Integrated Project of the 6th Framework Programme of the European Union.

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Introduction of UNSGAB/HELP on Water and Disaster

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Abstract

UNSGAB stands for United Nations Secretary-General's Advisory Board on Water and Sanitation, which was established as an independent body in March 2004 by United Nations Secretary-General, then Mr. Kofi Annan, to give him advice on water and sanitation issues that are essential to eradication of poverty and sustainable development. The founding chair was HE Ryutaro Hashimoto, the former Prime Minister of Japan, and the current chair is His Royal Highness the Prince of the Netherlands. The Secretariat is hosted by the Department of Economic and Social Affairs (DESA), United Nations.

It released the so-called Hashimoto Action Plan "Compendium of Actions" in March 2006 on the occasion of the 4th World Water Forum held in Mexico City, which covers the items in five key areas: financing, sanitation, monitoring and reporting, integrated water resources management, and water and disaster. In order to follow up the recommendation on water and disaster, the High-Level Expert Panel on Water and Disaster (HLEP) was established by UNSGAB, chaired by the Prime Minister of the Republic of Korea, Han Seung-soo, and co-moderated by the World Water Council (WWC), the UN Secretariat for the International Strategy for Disaster Reduction (ISDR), the Japan Water Forum (JWF), and the Korea Water Forum (KWF).

The HLEP consists of 21 members, including Director of ISDR, President of WWC, Executive Director of JWF, representative of FAO, President of World Water Partnership, Secretary General of WMO, Director General of UNESCO, representative of UNICEF, representative of World Bank, Director of ICHARM, and most importantly here, Lieutenant General Robert Van Antwerp, the chief hydrologist of the U.S. Army Corps of Engineers.

Thus, this is a top-down approach to solving global water problems, making politicians and top leaders commit for action and move national and international governmental mechanisms for implementation. As a product of a series of meetings, the report "Water and Disaster" (Figure1) was issued in March 2009 on the occasion of the 5th World Water Forum in Istanbul. The report is a collection of actions proposed, discussed and committed by those top leaders. It is not just a list of recommendations, but an action plan.

Action Plan

The HLEP calls for Six Urgent Imperatives, which promote the Hyogo Framework for Action (2005-2015):

1. Galvanize and mobilize before disaster strikes.
2. Prioritize systems to forecast, inform, alert and evacuate.
3. Incorporate disaster risk reduction and climate change adaptation as integral to development planning.
4. Improve disaster response.
5. Provide safe water and toilets quickly when disaster/conflict strikes.
6. Special crosscutting Initiatives:
    * Provide hydro-climatic data as public goods.
    * Large Delta States Network to tackle the negative impacts of sea level rise associated with ongoing climate change.
    * Initiative to identify underlying analytical and data requirements to meet climate changes that are likely to be highly uncertain and so as to support structural and non-structural measures for disaster risk reduction.

Under those six imperatives, there are 40 actions listed. All actions are composed of local/national or global action and our action. Our action indicates what the Panel does to initiate actions and monitor their development. ICHARM considers some of these actions very important; one is a strong emphasis on the idea that disaster management should be included in the development plan of a nation to attain economic growth. It urges:

Action Item Number 1

National governments to mainstream and integrate disaster potential assessment and risk reduction within their development plans to promote economic growth. (Our action is): Ask UN Secretary-General to invite member states to undertake the proposed action.

One of the concrete actions in relation to this line is to urge the OECD Development Assistance Committee to change its classification of disaster management from limiting it to solely a humanitarian task to include a development task, saying:

Action Item Number 28

OECD/DAC to no longer consider disaster risk reduction solely a humanitarian task. This would enable donors to increase their investment in preventative measures for disaster risk reduction. (Our action is): Request OECD/DAC to realize the proposed action.

The other actions important to both ICIWaRM and ICHARM are the promotion of early warning and preparedness such as:

Action Item Number 2

National governments to promptly develop people-centered warning systems, comprehensive flood risk maps, and assessments linked to communication systems such as cell phone networks. These systems would include observation and warnings for flash floods. (Our action is): Request WMO and UNESCO (via the International Flood Initiative) to assist governments in undertaking the proposed actions and invite international financial institutions to support the fulfillment of the proposed actions.

Action Item Number 03

The International Flood Initiative and international hydrological and hydraulic institutes to examine the efficiency and effectiveness of disaster prevention measures and develop disaster preparedness indices for implementation by local authorities. (Our action is): Request International Flood Initiative and international hydrological and hydraulic research institutes to examine the efficiency and effectiveness of disaster prevention measures and develop disaster preparedness indices.

Here, the International Flood Initiative (IFI) is a program jointly initiated by UNESCO, WMO, UNISDR, and UNU supported by many governmental and non-governmental organizations, inaugurated at the World Conference on Disaster Reduction in Kobe 2005. Its objective is to promote an integrated approach to flood management to take advantage of the benefits of floods and use of floodplains while minimizing the social, environmental, and economic risks. ICHARM assumes the role of its secretariat and promotes its implementation jointly with many other organizations, including ICIWaRM.

Assignment to ICIWaRM

The most important action in relation to this Nonstationarity Workshop and to ICIWaRM is the following:

Action Item Number 29

National and international hydrological institutes must take the initiative to identify underlying analytical and data requirements to meet climate changes that are likely to be highly uncertain and so as to support structural and non-structural measures for disaster risk deduction. (Our action is) Call key international hydrological and hydraulic institutes to realize proposed actions.

This is highlighted as one of three special cross-cutting initiatives, too. It is a great contribution to the world that ICIWaRM takes leadership on this action under the strong commitment of General Antwerp. In fact, it is part of IWRM exercise and indeed on the target area of ICIWaRM.

In addition to this action, there are six other actions in the recommendation in relation to adaptation to climate change. They cover such areas as needs of establishment of regional climate centers, promotion of national and global adaptation actions through UNFCCC, IPCC, and WCC, organization of workshops by UN regional organizations and regional development banks, start of North-South Dialogue initiated by G8 and OECD, and Large Delta States Network by delta states.

Concluding Remarks

The UNSGAB/HLEP action plan is a top-down approach initiated by ministerial level leadership of water-related disaster conscious policy makers. Their commitment is to make water and disaster a mainstream in a nation's decision-making process. This action plan is thus supported by an excellent basis. Nevertheless, the real implementation of the plan is in the hands of organizations, institutes, professionals, experts, officials, and many localities in practice. In this respect, the role of ICIWaRM is of central importance. ICHARM would like to support its efforts in any respect possible.

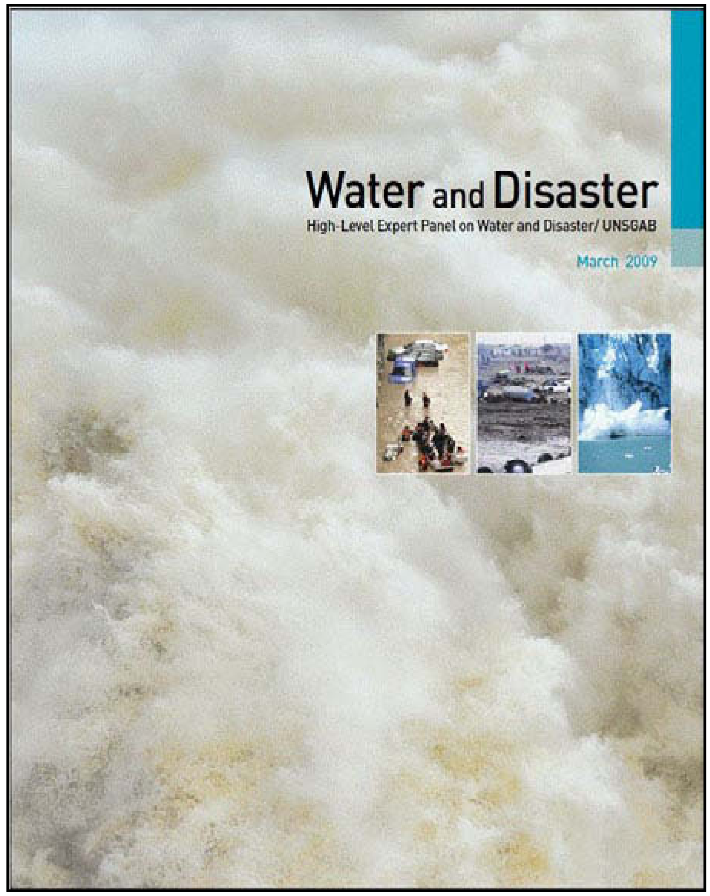


Figure 1. The UNSGAB/HLEP Report issued at Istanbul, Turkey in March 2009.

Biography

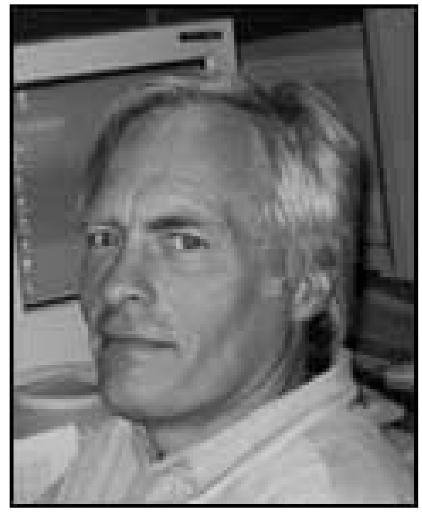
Kuniyoshi Takeuchi is Director of International Center for Water Hazard and Risk Management (ICHARM) under the auspices of UNESCO, Tsukuba, Japan since March 2006. He was a professor of Department of Civil and Environmental Engineering in Yamanashi University for 30 years till March 2007. He got his BS (1966), MS (1968) and Dr.Eng. (1982) in Civil Engineering at University of Tokyo, and Ph.D. (1972) in City and Regional Planning at University of North Carolina. His major field is hydrology and water resource systems. Interest includes reservoir operation, hydrological statistics, stochastic hydrology, distributed hydrological modeling, lake hydrology, radar and satellite hydrology etc. He served as a principal investigator of various hydrological research projects including that of Mekong River and Yellow River Basins. Currently he is involved in water-related disaster management, risk assessment, hydrological simulation for early warning and impact analyses of climate change on water-related disasters. He is the chair of the IUGG (International Union of Geodesy and Geophysics) GeoRisk Commission (Commission on Geophysical Risk and Sustainability) since 2007 and a member of IRDR (Integrated Research on Disaster Risk) Science Committee since 2009. He has been engaged in UNESCO IHP (International Hydrological Program) activities serving as the chairperson of IHP Inter-Governmental Council for 1998-2000 and IAHS (International Association of Hydrological Sciences) activities serving as president for 2001-2005. He is a recipient of JSHWR (Japan Society of Hydrology and Water Resources) Distinguished Contribution Award (2000) and JSCE (Japan Society of Civil Engineers) International Contribution Award (2009).

Workshop Summary

Workshop Summary I

Dennis Lettenmaier, University of Washington

Introduction



Back about 10 years or so ago, I spent a year at NASA headquarters, working with Pierre Morrell, which was an interesting experience, but Pierre would sit in these meetings, for two or three days, and at the end, he would always say, okay, so there are three things here. Everything was always three things. There were always three things.

I was actually close. I have four things that I extracted. One of them was actually what we discussed a bit in break-out group yesterday and was mentioned this morning, but my feeling is the hydrologic community really needs to develop an understanding of how to use nontraditional data for hydrologic predictions.

One of the things that I see, sitting here in the back of the room, is that the people who do things like frequency analysis, analytical methods, the sort of tried and tested things, tend to want to do things that adapt those, which is an obvious and natural thing to do, but the kinds of observations, the kind of modeling output and so on, that doesn't quite fit into that construct. They're sort of a reaction. You know, the GCMs aren't any good. They're not evaluated. We need to wait until they're more specific.

So let me give you just a little of my perspective on this. If you go and download the GCMs from the AR4 archive and take the global averages, okay, across the models, the lower plot is the global average temperature. It's the inner quartile, so it's -- out of 20 models, it's the 10 that are in the middle, and that's the global average temperature projection, anomalies relative to, should have been 2000. I'm not sure why that shifted, but it does go through a line at zero there at some point, where they are forced to be the same. But the point is, the anomaly spread is fairly small.

If you go and take all the models and take the range, that gray range in the lower plot, ends up being three or four times as wide. It's wider but it's still reasonably well constrained. And frankly, that, at the global level, has been reasonably well understood for a long time, okay.

The precipitation is the upper one, a little bit broader, but I mean, that sort of thing is reasonably well understood. Maybe the models are all wrong. We could have that discussion. But they tend to agree reasonably well.

Now, if we go to the scale of the continental U.S. and go overlay -- and this is precipitation for various scenarios -- and what this is for, this is for the 30 years that are centered on the year when the global average temperature reach of the models is increased by 1.0 degrees C.

Turns out that that, on average, is between 2030 and 2038, it does not make much difference at about 1 degree C which emission scenario you use. They start diverging later on, and you see this pattern which actually looks very much like what came of out Chris Mille's 2005 Nature paper, and kind of a replotting that was done of his results for one of his CCSCs, synthesis and assessment reports from a couple of years ago.

So what you see is this sort of characteristic divide. This is precipitation now. The browns are where they go down, the blues where they go up, and it's kind of a divide. This is basically for the median over GCMs, and then in parentheses, which you probably can't see from the back, is the range, is the inner quartile range, and the big numbers here are the -- they are changes in millimeters per year, and actually, I wouldn't do it exactly that way, because it confounds a little bit the drier parts the country with the wetter ones, but you do see this divide in precipitation.

If you do this for P minus E, which is runoff, what'll end up happening is the divide will kind of move north a bit, because the evaporation goes up with temperature as well, so the divide tends to move north, but you see the northeast looks wetter than the light blues up here and then down further in the south and the southwest.

Now, what you also see, when you go look at the ranges here, you've got most of these -- in fact, these numbers are all positive in this particular -- 13 to 45 millimeters per year change. When you get down here, they're almost all negative, and then where these lighter colors are, they straddle through zero a lot. There's a lot of uncertainty.

But, you know, this is taken across 20 GCMs, and what's happening here is that that global signature, where the range is relatively narrow, now you go try to put that over the continent, and the hydrologic regions and you get a lot more spread, and frankly, that's what I think this community is having a lot of trouble trying to understand what do we do with this sort of stuff which is really nontraditional information. It's further complicated by the fact that the models change over time, so this map, when they do the AR5 results, won't look exactly the same.

However, I think there's a lot of misunderstanding in this room, particularly amongst hydrologists, of the nature of the GCMs. And Geoff Bonnin and his flock pointed out, yes, there's a lot of problems with the models. The modelers really need to be talking to us. We need to be pushing them harder.

But it's a two-way street, and so I think there are a lot of people in this room who don't understand that when you go extract one of these GCM sequences for a hundred-year run for the historical past, that you can't expect it to match individual years. It's constrained only by the global emissions for that particular year, because the system's chaotic.

What you can only expect to do is in some probabilistic context to match the climatology, and that's the kind of analysis that has to be done. And frankly, the models have problems. Some of them do better than others. But many of us in this room haven't even looked at the output.

Now, you did a back-of-the-envelope calculation, and for a hundred year sequence for one variable for one model, it's about 20 megs, and the things are archived. They're very easy to extract. You get the monthly output. So working with it is really not that big a deal, and probably having a little bit more familiarity with the nature of this kind of information is something that this group needs to do.

So what I've seen in general going on is that there's been some interesting work looking at trying to deal with certain kinds of nonstationarity as we've observed them in the historic record.

In terms of land cover change, some of these basins clearly have changed. Rick Vogel has done a little bit of work in how you subscript by T some of the parameters and frequency distributions and then estimate those so that you can get frequency estimates that are relevant to today, and there's a class of problems for which that's important.

And it's the ones, frankly, where there's some decision or estimates being made other something where that distribution isn't likely to change very much. We saw an example having to do with extent of snow cover and freeze frost status on northern haul roads, for instance. What's the likelihood that the road is still going to be serviceable on May 15th or something.

Well, you probably wouldn't estimate that using data that's current up to 1970 or something, because everybody pretty much recognizes that's changed, and if you have some estimate that's sort of adjusted and done the best way you can to incorporate the historical data, incorporating some kind of shift, then that makes a lot of sense.

If you're making some sort of plan for a structure that's going be to be there for a long time and for which economic life is some number of decades, then you really have to think about weather and information about how things might change in the future can be incorporated.

And it may be that our traditional estimate methods get the best estimate of the frequency distribution and do some benefit-cost analysis. And we really have to not be just reacting and saying, you know, these models are such poor resolution, they're this, they're that, we can't use any of it. We're just going to resort to doing what we've been doing for a long time.

The second thing. We need an academy study to review the whole scientific basis for the flood risk estimation in this country. I think personally it's time to give Bulletin 17B a decent burial and move on, and I think we have a good opportunity here because nothing's been done with it in approximately 25 years.

Now, what the solution is? Maybe an academy panel with the appropriate charge comes back after looking at it all very carefully and saying, we immediate Bulletin 17C. The foundation for this isn't too bad, but it needs adjustments for ways to go deal with certain kinds of nonstationarity and so on.

Or maybe they say the world's changed in 25 years. We have longer hydrologic records. We have a lot of spatial data, information on land cover change. We have information on climate models and a lot of other things that we didn't have access to 25 years ago. It's time to rethink the whole base.

That's the sort of thing that a committee would be charged with doing. But that would then give the Federal agencies the basis to move forward. I don't think that this interagency committee that we heard from are in a position to have the clout at the top of the agencies where the directive would have to come from to do something like this. So I think it's time to move to. To use Gene Stakhiv's characterization, not mine, let's blow it up and start over.

And here I'm borrowing unabashedly from some comments and rephrasing that Bob Hirsch made at the academy meeting last week, but the scientific community needs to make an effort to understand the nature of ongoing hydrologic change. We have not done nearly as good a job as we should be doing to understand what the hydrologic records have been telling us in conjunction with ancillary information of land cover, climate, and so on. And the funding agencies have to be convinced that this is a necessary research enterprise.

Now, I'll point that that NSF has just, as of yesterday, come out with a solicitation on water climate and sustainability. It's words about like that. And it's joint across the geo sciences, engineering, biological sciences -- and somebody else is in there -- I think social sciences directorate.

I'm not quite sure whether this type of stuff would actually fly there, because when you read carefully, everything has gone to, you need big teams, you have to have a social scientist, you have to have a biologist, and so, all of which is great, but it tends to diffuse the effort a little bit. I'm happy to see that engineering is on board with that because engineering has basically gone AWOL with respect to water resources issues for many years at NSF. So maybe this will be the avenue to move things forward.

But just real briefly, this is updated, Harry Lins was good enough to provide this from the Lins and Slack paper in 1999, with the updated. It doesn't look a lot different, and you know, seeing the low part of the distribution. There's a lot of up trends across the country. There's not nearly as many down trends. And then when you get up to the high end, the annual maximum series, that's when you have as many up trends as down trends.

Rich Vogel's been looking at a wider set of stations that don't have quite the same constraint with respect to regulation and so on, but he sees something very roughly equivalent. There are something like -- and Rich can correct me if I'm mischaracterizing his work, but it looked like there was 10 percent or so of those stations where they're clearly up on the flood end with things going on. Land cover seemed to be implicated in a lot of them, but there's a lot of work to be done to understand what's really going on there.

Also, when you look at these sort of things spatially, there's a very interesting signature. I think Bob or somebody in their talk might have mentioned this business in the upper Midwest and their low flows. We saw in our 1994 paper, and it's been apparent in studies since then. I don't think we understand exactly what's going on there; is that a warming signal, groundwater changes, exactly what's happening there, and we really need to understand better than we do.

Over on the flood end, Mike Dettinger made a very good comment that, looking at the mechanisms for floods and how those might or might not be changing is something that we need to do a better job on.

And we now have the observational data sources, at least for large-area floods, to look at things like the real analysis and so on that goes back 50-plus years on some of them, they're certainly good enough to understand something about the large-scale atmospheric features that go along with at least the larger plugs.

This is certainly the case along the west coast, but for many other parts of the country, could be possible as well. I don't think as much has been done there as could be.

Katie Hirsch gave a talk last week, looking at floods in the Southwest, and her comment was the same nature. There's basically three different types of mechanisms in the Southwest that can lead to floods, and the mix of those has been changing, and there's information and understanding how the floods came about that we're not exploiting as much as we can. And I think we should.

Now, this is my provocative statement, and I say this, having worked in this field a bit, but my claim is understanding the nature and physical bases for low frequency time series variability is an interesting scientific problem but it's not the main one facing the community. And I'll tell you why.

This is a synthetic time series, fractional Gaussian noise, H over .5 is white noise. H over .7. This is the Hurst coefficient. For those of you who aren't familiar with the work that goes back into the 60s and 70s, it was originally based on work that Hurst did on Nile River flows where he noted that the sequences of flows could not really be explained by random variability. They tended to persist longer than you would expect in any kind of random or even the low persistence time series, and so there's a variety of ways of synthesizing these things.

The short version of this, though, is that, well, you're looking at some part of the time series. You can imagine up trends and then guess what, they go down, and what it implies is that, if you sit around and wait long enough, things will come back.

The reason I don't think this is terribly relevant to many of our problems, is that if you look at the case, for instance, of an urbanizing watershed, and we see changes, say, in the flood frequency and mean flow, do we really expect that if we sit long enough and wait, that things going to get back to where they were?

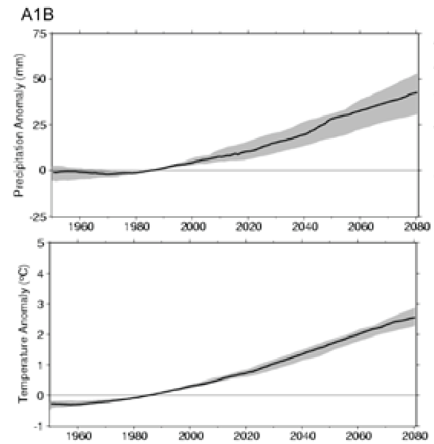
I submit that in many, if not most, of the cases that we're looking at, this isn't the case, and that's not a terribly productive enterprise, interesting that it is, and where they are, I will grant specific applications and interesting cases. That's not the primary problem, and it sort of obscures the issue of how we deal with nonstationarity.

NOTE: *This is a transcript of the author's remarks at the workshop that has not been reviewed or edited by the author.*

Biography

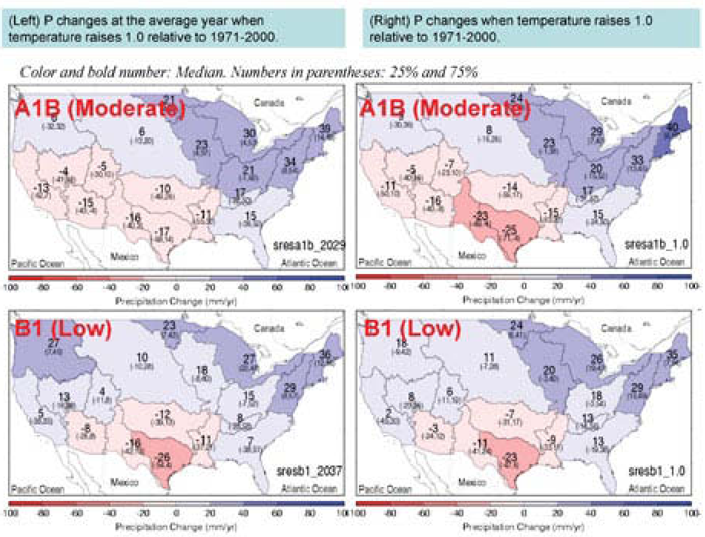
Dennis Lettenmaier received his B.S. in Mechanical Engineering (summa cum laude) at the University of Washington in 1971, his M.S. in Civil, Mechanical, and Environmental Engineering at the George Washington University in 1973, and his Ph.D. at the University of Washington in 1975. He joined the University of Washington faculty in 1976. In addition to his service at the University of Washington, he spent a year as visiting scientist at the U.S. Geological Survey in Reston, VA (1985-86) and was the Program Manager of NASA's Land Surface Hydrology Program at NASA Headquarters in 1997-98. He is a member of the American Geophysical Union, the American Water Resources Association, the European Geosciences Union, the American Meteorological Society, and the American Society of Civil Engineers, and the American Association for the Advancement of Science. He was a recipient of ASCE's Huber Research Prize in 1990, and the American Geophysical Union's Hydrology Section Award in 2000. He is a Fellow of the American Geophysical Union, the American Meteorological Society, and the American Association for the Advancement of Science, and is a member of the International Water Academy. He is an author or co-author of over 200 journal articles. He was the first Chief Editor of the American Meteorological Society Journal of Hydrometeorology, and is currently an Associate Editor of Water Resources Research. He is the President-elect of the Hydrology Section of the American Geophysical Union. His areas of research interest are large scale hydrology, hydrologic aspects of remote sensing, and hydrology-climate interactions.

1) The hydrologic community needs to develop an understanding of how to use non-traditional data in its hydrologic predictions



The anomalies have been filtered using 30-yr moving average.

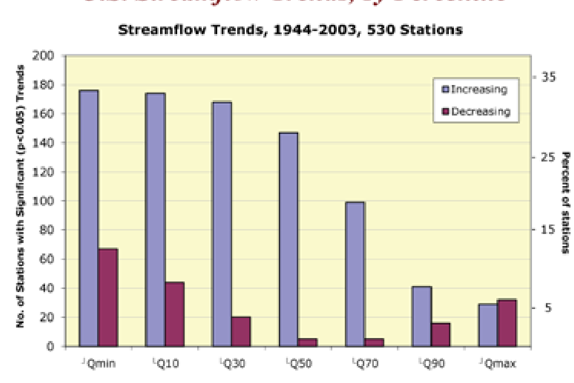
The anomalies for each model are relative to the current climatology (the 30-yr moving window at 1971-2000).



We need an NAS study to review the scientific basis for flood risk estimation (time to give Bulletin 17b a decent burial, and move on)

The scientific community needs to make an effort to understand the nature of ongoing hydrologic change (and convince the funding agencies that this is a necessary research enterprise)

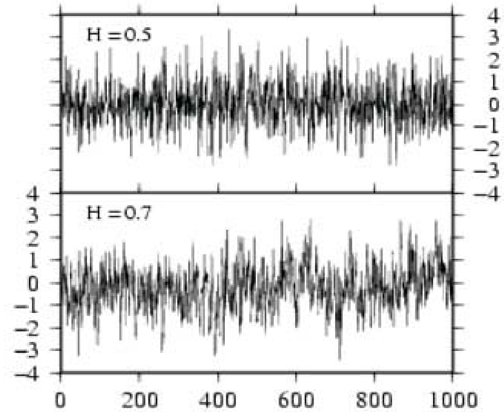
U.S. Streamflow Trends, by Percentile



USGS

Source: Updated from Lins and Slack, 1999, Geophys. Res. Lett., p. 229

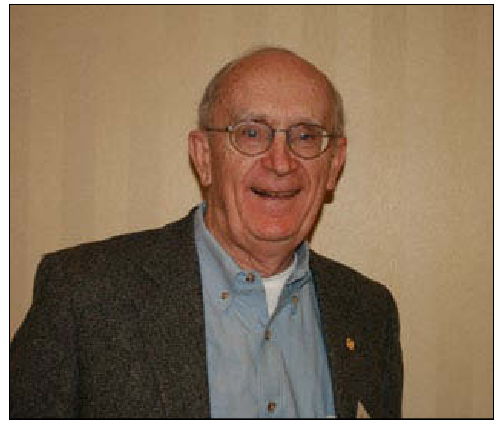
Understanding the nature, and physical bases for, low frequency time series variability is an interesting scientific problem, but it's not the main one facing the community



If Stationarity is Dead, What Do We Do Now?

Gerald E. Galloway, Glenn L. Martin Institute Professor of Engineering, University of Maryland

Introduction



The issue? Cedar Rapids, Iowa, was badly hit by the 2008 Midwest Flood. Today, city leaders and the Corps of Engineers are conducting a study to examine the feasibility of providing a flood risk reduction project for the city to mitigate the potential losses from future floods. In order to be in line for Congressional authorization, they plan to complete this study by late summer 2010. Their challenge is to determine the expected flood flows in the Cedar River over the next 50 to 100 years. Two decades ago they would simply have turned to the Interagency Advisory Committee on Water Data Bulletin 17B (US Water Resources Council, 1982) to produce an estimate of the 100-year flood flows, knowing that stationary permitted them to create a statistical estimate of their threat. Over the past 2 1/2 days, distinguished scientists have discussed the difficulties they face in determining future flood flows if stationary is dead. But then, what flood flow figures should Cedar Rapids planners and the Corps use in preparing their study report? They, like many other planners across the country, can't wait years for hydrologists and climatologists to come to some mutually agreeable solution. They need answers now.

The Workshop

The workshop was convened to, among other things, discuss the need for new ways to conduct hydrologic frequency analyses under nonstationarity and to discuss a range of potential alternatives for dealing with nonstationary in both the long and short term. I was asked to give a practitioner's perspective on what came out of the discussions. I am not a hydrologist or a climatologist, but someone who works closely with those who need the sound advice of such scientists in order to move ahead with a variety of water resource activities. I recognize that there are no simple solutions to dealing with the uncertainties we now face with climate change and other possible contributors to nonstationarity. However, I ask scientists to recognize that while they are developing answers to the difficult questions they face, they must also assist the practitioners in dealing with the calculations they must make during this interim period. Solutions today are already too late.

Workshop Thrust: Participants in the workshop made many insightful points over the course of the meeting and common themes were evident.

Nonstationarity, in many forms, is something that is here and we have to live with it.

- Nonstationarity – Get over it!
- God, grant me the serenity to accept the things that I cannot change…
- Nonstationarity applies across more than climate-hydrology.

There is a need to identify solutions quickly.

- We don’t have the option of waiting.
- Got to get to work on solutions for today… look at no regrets, flexibility, and ability to adapt over time.
- There will always be a bigger flood coming.

There is a need to proceed forward with attention to good science.

- Don't help people do wrong things more precisely.
- Looking for a linear trend is reasonable…

- Trendy behavior is not equal to nonstationarity; period of analysis matters.
- It may not be reasonable to expect we observe changes as fast as they are happening.
- Warts and all, GCM based flood projections give us some insights.
- We should be focusing on possible changes in flood mechanisms for indications of the future, in both models & data.

Change will bring about new approaches in planning.

- Dynamic design – pick the plan that is effective in meeting multiple plausible futures.
- We need a new multi-disciplinary attack on water resources planning and management – we need a new paradigm.

The Water Box

It is important to recognize that the implications of nonstationary extend far beyond the hydrology community. In its World Water Development Report 3, the UN World Water Assessment Program (2009) describes a water box in which water sector managers of all disciplines carry on their activities. Nonstationarity is of concern to everybody in the water box. Above this water box are the actors who influence the broad social economic policies that affect water. Included in this latter group are the political forces, business and economic actors and those representing civil society. Frequently those in the water box are oblivious to the far-reaching actions of those outside the box. The death of stationary, if it is dead, will ultimately mean as much to those outside the box as in the box and this linkage must be recognized as we move forward. The scientific community's ability to obtain resources, focus its efforts, and to achieve results, is in large part dependent on people outside the water box. So it is imperative that those of us in the water box remember the role that is being played outside the box. Much of what I have heard during the workshop is directed at how we are going to manage activities within the water sector, and very little has been expressed about how we influence those groups that may ultimately drive our actions.

Throughout the workshop I observed dedicated individuals focused on developing solutions that would benefit not only their disciplines but society as a whole. It was clear that things are different today than they were yesterday. Climate change has inserted new challenges and we are finding that the way we have done business in the past may not work in the future. Paradigms, procedures, and models on which we relied may no longer be as useful as they were in the past. David Raff, in his presentation on flood frequency based on climate projections (2010), noted that while scientists may now be moving forward to face an uncertain future, they frequently have their heads turned to look at the past. This could be dangerous if the road ahead is full of obstacles.

The discussions highlighted strong differences of opinion between hydrologists and climatologists as to what data can be gleaned from on-going climate change research. The differences have risen, in some cases, to the level of a Hatfield-McCoy dispute. If not a gulf between the disciplines, there is certainly tension, and the situation is not getting better. Each group seems to believe that it is steering the proverbial log floating down the river and indicating that without its expertise the journey will not come to a proper end. Perhaps if the two groups would come together, their coordinated effort might be able to control the rudder that will steer us into the future. Several times discussants noted that it would be very useful to bring both groups together under the same tent with a common funding stream that supports the needs of a joint effort. If there is not some movement in that direction, coordinated and comprehensive solutions will be a long time in coming.

We also face a Tower of Babel. Roger Pulwarty, NOAA, pointed out that we in the water sector have a lot of words in use but we don't have agreement on their meaning. Most are familiar to all of us:

Acceptable/Tolerable Risk	IWRM	100-year Flood
Actionable Science	Collaborate	Robustness
Scenario	Projection	Prediction Risk
Adaptive Management	Extremes	Deterministic
Stochastic	Uncertainty	Heuristic
Decision Support	Flood Management	

If we are going to work together and if we expect to communicate out of the water box, there is clear need to collaboratively determine how we are going to use the terms that are that are most important to our progress.

Observations

The meeting's discussions lead me to offer a few observations:

- We must all recognize that climate change and nonstationary are more than simply topics for an intellectual discussion. These discussions will lead to decisions that have significant economic ethical and moral dimensions. These decisions will typically be made by those who are outside the water box, but they must be informed by good science. We must also understand that the decisions we make today regarding the design of our water resources infrastructure will be reflected in a built environment that may be with us for more than a century. New York City's water supply system today is the result of decisions made 100 years ago. In addition, with the increased attention to sustainability, our decisions must consider whether structural or nonstructural approaches are best suited for the period ahead. We cannot continue to kick the ball down the field. We've got to be able to advise decision-makers today what to do and to make sure that what we tell them is reasonable. A failure to do so could well put people and property at risk. The new scientific insights and the resulting recommendations from the scientific community will influence the economic viability of communities, and the quality of life and safety of the many people, frequently the economically and socially disadvantaged, who live or work in a floodplain.
- We must also recognize that the way we do business is changing. Seventy years ago our approach to dealing with floods was to control the water by keeping it away from the people through dams, levees and channels. The design of all of these facilities relied heavily on the work of hydrologists and climatologists. Today, it is not acceptable to rely solely on one means of reducing flood losses. The combination of structural and nonstructural means is the focus of flood risk reduction programs at both the federal and state level. Figure 2 illustrates California's FloodSAFE program (Mayer, 2008). Each of the steps in the staircase represents an action that is or will be taken by some organizational element as part of the overall program to reduce the risk of flooding across California's floodprone areas. Wise decisions on each of these actions will require access to and use of hydrologic data. While they may be able to adapt several of the nonstructural elements of such a program as conditions change, decisions about how high to build a levee or a floodwall today require specific information on which to base this decision for a project that may be in place for decades.
- The water community is too bureaucratized. We work in stovepipes and see ourselves hemmed in by the authorities that were dealt us by the Congress decades ago. It is reasonable to assume that the Congress is more comfortable with stability than change but, it is not reasonable to assume that the Congress, once properly informed, would not consider modifications to authorities to deal with the changes that are occurring. Amendments to the organizational authorities are made every year (and sometimes in the middle of the night). If there is need for change within the water box, we need to be getting that message to the Administration and those others who get things changed. The courts frequently point out where conflicts and overlaps exist in authorities and urge the Congress to deal with these issues.
- We need solutions now. If it's not possible to reach final conclusions on how to deal with the changes that are occurring, then we need to have some clearly defined interim procedures. The better is clearly the enemy of the good. Tomorrow always turns out to be months or years away. The professionals dealing with Cedar Rapids need something next week not next year.
- The workshop clearly felt the absence of discussion of societal and environmental implications of climate change and their relation to water planning and management. We surely must consider what a failure to accurately plan for too much and too little water will mean to the economically disadvantaged, minorities, and the elderly. As climate changes, so will the ecosystems around us. What actions must be taken to deal with these changing ecosystems and what data must we produce in order to support these actions?
- We need to look at the impact of potential changes on planning.
    * Our work with hydrologic nonstationarity must also take into account related nonstationary activities such as population growth and increased development and their impact on basin hydrology. Several states are now experiencing changes in channel morphology. Current FEMA regulations do not permit flood insurance rate maps to consider these ongoing changes, thereby portraying yesterday's conditions on a map people expect to use for tomorrow's planning.

* Marc Waage (2010) pointed out that much of our planning today is conducted inside a cylinder, expecting that the relationship among the many variables with which we must work will remain constant over extended periods of time. In reality, he noted, we need to be doing conical planning and recognize that with time there will be many changes and that these changes will be in directions we cannot now predict. Conical planning represents a new paradigm. Water planners have been tied to the output of the Harvard Water Program which provided us an effective planning framework for more than five decades. Casey Brown (2010) indicated that it is time to move in a new direction and to consider planning factors that are important to the 21st century and leave behind some factors whose worth is now in question. The next generation must be able to deal with nonstationary input in the development of solutions that are politically feasible and sustainable. There will be a demand for tools that will permit us to better forecast climate, monitor the environment, improve our modeling and better describe our economic solutions. Risk management will guide most actions and flexibility will be essential. Who is going to stand up such a program?

* There will be many difficult choices to make and the demand for decision support systems that are more transparent, complete, and realistic will certainly increase. When major decisions have to be made, it is important that those outside the water box understand the decisions they are making and have accurate and timely information to support these decisions. The Corps' efforts with Shared Vision Planning (see www.svp.iwr.usace.army.mil/) illustrate how making black boxes transparent can substantially improve public involvement in planning activities.

* The ongoing revision by the Administration of the 1983 Principles and Guidelines for Water and Related Land Resources Implementation Studies (US Water Resources Council 1983) was discussed in several presentations. This effort merits the participation of the scientific community in the review process. Participation in this process offers one way of getting out of the water box. The current Principles and Guidelines focus on national economic development as the sole objective of water resource project development and is limited to work by the Army Corps of Engineers, the Bureau of Reclamation, the Natural Resources Conservation Service, and the Tennessee Valley Authority. The proposed Principles and Guidelines extends the reach of the document to all federal agencies involved in water resource project development and expands the objectives of such development to include environmental and public safety objectives as well as social justice.

* We spent considerable time discussing how we can improve the preciseness of the computations of the flows that result from rainfall and snow melt events. We continue to avoid defining what is tolerable or acceptable risk in the flood zone. We are very concerned about the ability of our structures to resist the forces they will encounter, but fail to determine what level of protection is enough for a given geographic situation and who decides how large the structures should be? Because the National Flood Insurance Program uses the 100-year flood event to define a special flood hazard area for insurance purposes, the 100-year event has become a de facto standard for other activities in the floodplain. Yet 42 years ago, when Gilbert White and others gathered at the University of Chicago to examine what might be an initial standard for the flood insurance program, they indicated that the 100-year designation was an opening approach and should be changed over time to reflect regional differences and experiences. More recently, Bob Hirsch, Tim Cohn, and William Kirby (20024) noted that "the hundred year flood discharge Q0 .01, is an elegant abstract concept that presents complications when applied to real-world problems." Shouldn't the water sector, in the midst of dealing with stationary and nonstationarity, also focus on developing a new approach to defining flood standards for this century? We must also ask what happened to the use of the Standard Project Flood (SPF) in designing flood damage reduction projects. From 1936 until the late 70s it was the standard used by the Corps for protection of urban areas. Several participants indicated that politics and economics moved the Corps of Engineers away from the use of SPF because lower standards are more financially feasible. Is it time to move back?

* In our rush to deal with stationary and nonstationarity, we often neglect close examination of paleohydrology. Much can be learned from examination of floods that have occurred in the past. The European Community stresses identification on flood maps of historic flood events so that those who live in the flood zone will understand that what has already happened could happen again.

* There is a clear need for attention to the human resources involved in dealing with climate change and nonstationarity. We have lost a great deal of the technical capability in our research operational elements as both federal and state science organizations have downsized. The baby boomers, who have the critical institutional memory, are now retiring and the bench is very thin. Agency leaders need to understand that if we are going to be successful in

dealing with the changes that are surrounding us, they are going to have to find the resources to build the organization that will be required in the future.

* As previously discussed, there is need for a dynamic planning design and engineering process that is different than the one we are using today-the cylinder versus the cone. Getting those who are accustomed to working one way to shift to a new paradigm is not easy and we need to prepare and develop means to accomplish this cultural shift.

* Attention to research, data collection, and monitoring continue to wane. On the other hand, we should not expect governments to support one million flowers blooming when, perhaps, a lesser number would provide the robust research that is needed. As scientists, you need to assist in focusing research where it will provide the highest level of return and eliminating those programs, as painful as that may be, that are redundant or ineffective. During this conference many have spoken to the divide that exists between climate and hydrologic research. Given the challenge with resources, it is time to ensure that work is conducted jointly?

* Unfortunately, climate change has been politicized. Statements by scientists are being challenged on a regular basis. Who determines the correct answer? In the political world, compromise to achieve consensus is a way of life. In science, through the peer review process, you seek validation of your results. As we deal with stationary and nonstationarity, I would expect that we would always seek scientific agreement versus political consensus.

* The revision of Bulletin 17B has been going on for many years and publication of the revisions appears to be a long way off. Given the nonstationarity issue, should we continue with 17B or move in another direction? A recent report by a National Research Council committee (2009) indicated that advantage of gathering higher quality topographic data far outweighed potential improvements in hydrologic information. Will nonstationarity change this conclusion? In moving to a risk based approach to flood damage reduction more emphasis will be placed on assessment of the probability of successful operation of the myriad systems that today mitigate the impacts of floods. Will the revision of 17B significantly affect these conclusions?

* It is apparent from discussions in the workshop that senior leaders in the agencies don't appreciate the challenges that could arise from the death of stationary. The hydrology community needs to put effort into educating these leaders about the issues, how you are dealing with them, and what their role might be in developing solutions. You need to involve them in what you are doing to the point that they are able to contribute to the solutions you seek. These same managers must recognize that in dealing with the uncertainties you face that they must be flexible, adaptive, and above all, risk tolerant. They are certainly not there now. Again, there is a call for education.

In Sum

After 2 1/2 days of discussion, it is clear that the assembled hydrology community has yet to reach an agreement on replacing the assumption of stationary with that assumption of nonstationarity. Today, hydrologists around the nation are continuing to use techniques that assume stationary. New flood maps and project designs are being based on the assumption of stationary. I understand that there are many challenges in coming to grips with a shift from stationarity to nonstationarity. Climatologists, especially those deeply involved in climate change speak in a convincing manner about the changes that are taking place. On the other hand, hydrologists are skeptical that, after reviewing the data they have gathered, there is sufficient evidence of change in river flow characteristics. The gap between these two opinions does not seem to be narrowing. Caught in the middle are those who must proceed with the design of today's projects, projects that may be in use for the next half-century or more. While it is important for the hydrology community move ahead carefully in the development of new approaches, it is also important to recognize the immediate needs of practitioners who will use hydrologic information, and the interests of those who will live for an extended period with the projects that they are developing. What advice do you give Fargo and Cedar Rapids in the face of this diversity of opinion?

At what point, if any, do you shift from Bulletin 17B to something different? Who will make this decision and how? Given the myriad federal agencies involved and the diversity of university opinion, how will this be accomplished? At present, the water box is neither an efficient nor an effective place to operate, and, as a result, those outside the box are not well served. President Obama's Administration is pushing collaboration within the federal government and between the federal government and outside agencies. It should be evident to all of those who have participated in this workshop that your part of the water sector must increase the level of coordination and collaboration if you are to effectively serve those who rely on your scientific acumen. They cannot wait much longer for advice on how to deal with this uncertain hydrologic future.

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Biography

Gerald Galloway is a Glenn L. Martin Institute Professor of Engineering and an affiliate professor of Public Policy at the University of Maryland, College Park. A civil engineer, public administrator and geographer, has served as a water resources and flood mitigation consultant to a variety of national and international government and business organizations, is a member of the Louisiana Governor's Advisory Commission on Coastal Protection, Restoration and Conservation, and recently chaired an Interagency National Levee Policy Review Team for FEMA and an independent review panel examining flood challenges in California's Central Valley. He was a principal investigator for FEMA in the 2006 study of the adequacy of the National Flood Insurance Program's 1% flood standard. From 2007 to 2008 he was the Maas-White Scholar at the Corps of Engineers Institute for Water Resources.

He served as a Presidential appointee to the Mississippi River Commission from 1988 to 2005 and the American Heritage Rivers Advisory Committee from 2006 to 2008. In 1994, he was assigned to the White House to lead a committee in assessing the causes of the 1993 Mississippi River Flood. During a 38-year career in the military he served in various command and staff assignments in Germany, Southeast Asia and the United States, retiring in 1995 as a brigadier general. Prior to the University of Maryland, he was Vice President for Geospatial Strategies, ES3 Sector of the Titan Corporation. From 1998-2003, he served as Secretary of the United States Section of the International Joint Commission (IJC), Washington, DC, an independent binational organization charged with preventing and resolving transboundary air and water quality issues disputes between the US and Canada. He has testified before committees of the US Congress, and state legislatures, appeared on national television and radio and has spoken to numerous organizations in the US and abroad. He has lectured and written extensively on the management of water resources and public involvement in water resources decision making.

He is an Honorary Diplomate of the American Academy of Water Resources Engineering, a Distinguished Member and Fellow of the American Society of Civil Engineers, a Fellow of the Society of American Military Engineers, and a member of Association of American Geographers. In 2007 he served as president of the American Water Resources Association. He is a member of the Board of Trustees of the Natural Heritage Institute. He has served on eight committees of the National Research Council and is a member of its Water Science and Technology Board and the Disaster Roundtable. He is a graduate of the Military Academy and holds Masters Degrees from Princeton and Pennsylvania State Universities and the US Army Command and General Staff College, and a doctorate in Geography from the University of North Carolina at Chapel Hill.

In 1991, he was presented the SAME Bliss Medal for contributions to engineering education and, in 1995, the Silver DeFleury Medal by the Army Engineer Association. In 1998, he was given the Association of State Flood Managers' Goddard-White Award. In 2001, ASCE presented him the Civil Government Engineer of the year, in 2002 the Presidents' Award for service to the country, in 2008 the OPAL award for lifetime achievement. In 2004 he received the US Geological Survey's John Wesley Powell Award, the Golden Eagle Award from the SAME Academy of Fellows, and the Julian Hinds Award from the Environmental and Water Resources Institute of ASCE. In 2008 he received the Norm Augustine Award from the American Association of Engineering Societies and, in 2009, the Warren Hall Medal from the Universities Council on Water Resources. He is a member of the National Academy of Engineering and a fellow of the National Academy of Public Administration.

Workshop on Nonstationarity, Hydrologic Frequency Analysis and Water Management

Summary and Recommendations
A Practitioner's Perspective

January 15, 2010
Boulder, CO

Gerald E. Galloway, PE, PhD
Water Policy Collaborative, University of Maryland

Notable Para-Quotes

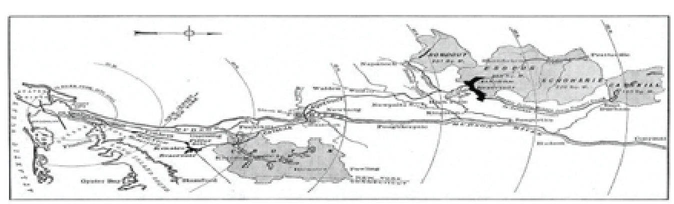
- Nonstationarity – Get over it!
- God , grant me the serenity to accept the things that I cannot change…
- Nonstationarity applies across more than climate-hydrology
- We don't have the option of waiting
- Got to get to work on solutions for today don't get too precise: look at no regrets, flexible, and ability to adapt over time
- Don't help people do wrong things more precisely
- Looking for a linear trend is reasonable…
- Trendy behavior is not equal to nonstationarity; period of analysis matters
- but can't say for sure

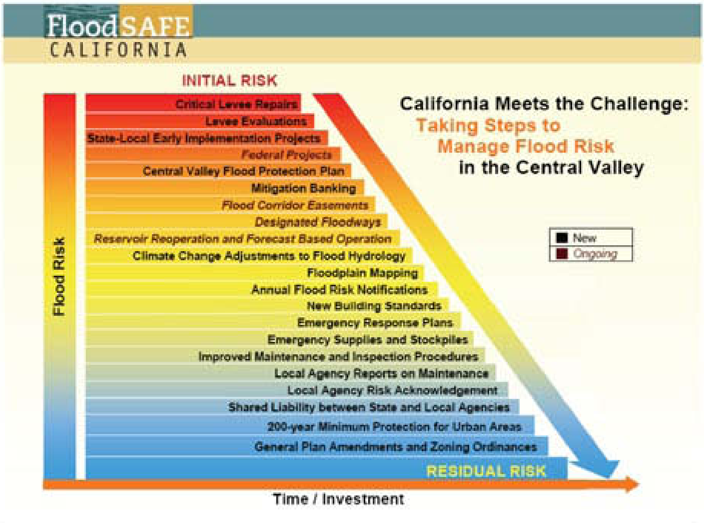
Notable Para-Quotes

- There will always be a bigger flood coming
- It may not be reasonable to expect we observe changes as fast as they are happening
- Warts and all, GCM based flood projections give us some insights
- We should be focusing on possible changes in flood mechanisms for indications of the future, in both models & data
- Dynamic design – pick plan that is effective in meeting multiple plausible futures;
- We need a NEW multi-disciplinary attack on water resources planning and management given the high degree of uncertainty – need new paradigm

General

- **Climate change and nonstationarity are more than an intellectual discussion topic and need to be seen as such. The issues have economic, ethical, and moral dimensions.**
- **We may have live with today's infrastructure decisions for 100 years and must keep that in mind in our discussions on whether to go structural or nonstructural.**





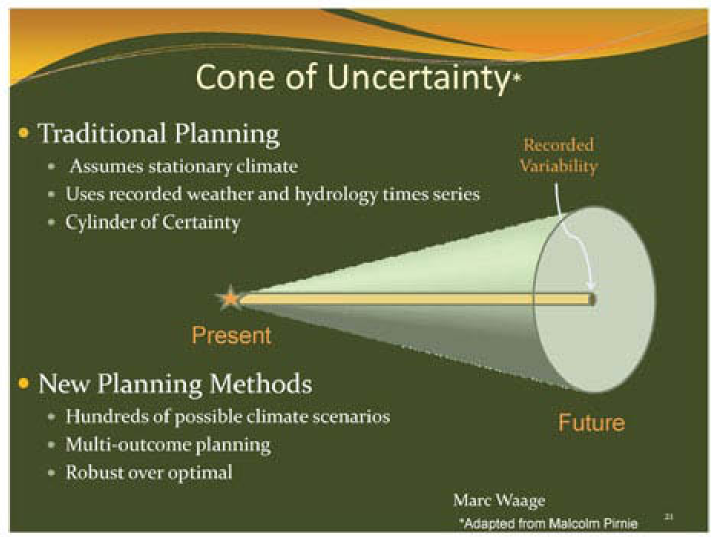
General

- The water community is too bureaucratized. It is doing things because of what it thinks it is what Congress wanted and believe they can't be changed. Go for it!
- Need some solutions now . May have to go with interim procedures - better is enemy of good.

REMEMBER CEDAR RAPIDS!!

Planning

- There was absence of discussion of social and environmental implications of climate change and relation to water planning and management. Need to include
- Planning needs to deal with "other" non-stationarity
- Conventional planning is so 'yesterday' and cylindrical
- Need new paradigm and support/education/learning for it



New Tools, New Harvard W.P.?

Harvard Water Program	**Next Generation**
	Nonstationarity
Welfare Economics	Political feasible solutions
Rational consumers/Neo-Classical Economics	Bounded rationality
Infrastructure system design	"Sustainability"
Optimal Solutions – Top down planning	Tools
Tools	Seasonal climate forecasts (uncertain)
Synthetic Streamflow	Environmental Monitoring (RS)
Optimization/Simulation	Consensus Building
Benefit Cost Analysis	Agent-based modeling
	Economic Mechanisms and derivatives
Reliability	Risk Management/Flexibility

Planning & Water Management

- Tough decisions ahead; Need more useful decision support tools
- Principles and Guidelines Document does matter All need to participate in in review process.
  - In absence of national policy, P&G provides national objectives
  - If proposal is accepted, needs to be used

Planning & Water Management

- Flood standards or policy don't exist - need to develop rational approach for future.
  - Don't consider catastrophic events – AAD is good for economists, not floodplain residents
  - Don't consider historical major floods
  - Risk management requires definition of tolerable/acceptable risk
  - Politics and economics drove unknowing morph from SPF. PMF to economic target or 100-year
    - 100 year is an insurance rating level –not a standard

WE SLICED THE BALONEY TOO THIN

Human Resources

- Lost technical capabilities in operational elements. Got to build capacity – the bench and the new team.
- We need to do dynamic planning, design and engineering but that will require people to change their ways – not easy. Prepare.

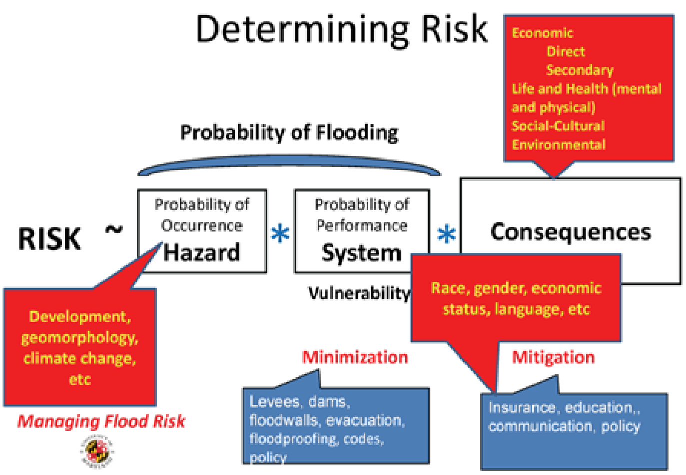
Science

- There are inadequate resources devoted to needed research. Need to appropriately resource climate-meteorologic-hydrologic-planning and management research..
- Can't support a million flowers blooming (maybe 100,000). Got to focus.
- Need to drive through to best answer. Consensus may not work!

Science

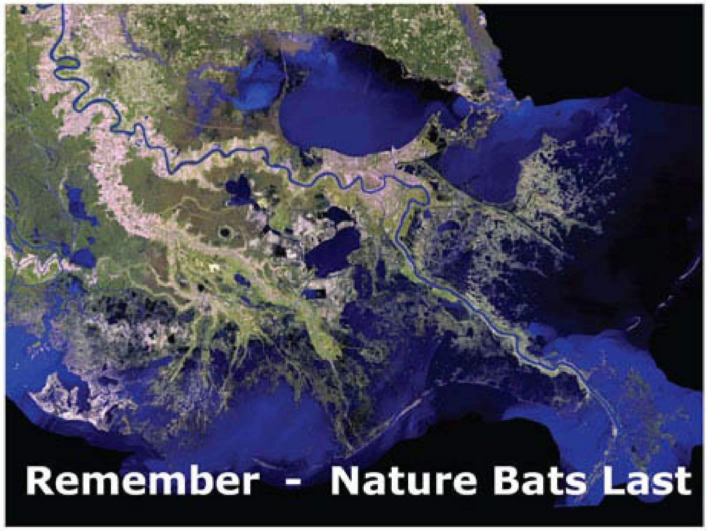
- No agreement but need one on whether we replace assumption of stationary or continue to use it as appropriate - it allows us to do many things
- Have the talent do work (but need more)
- Seriously neglecting monitoring and data analysis. Need to make cogent case for resources.
- Science decision chain not clear. Need to identify who decides and why.
- How important is 17b in risk assessment? Need to either fish or cut bait.

Determining Risk



Organizational Management

- Senior leaders don't understand challenge. Need to educate and court senior leaders
- Management must be flexible, adaptive, and risk tolerant. Not there now. Managers need to address how adjust to change
- Agencies unnecessarily tied to authorities. Counsels rule the world. If authority does not make sense, get it changed
- Water box is neither efficient or effective. Need collaboration among and within agencies and community

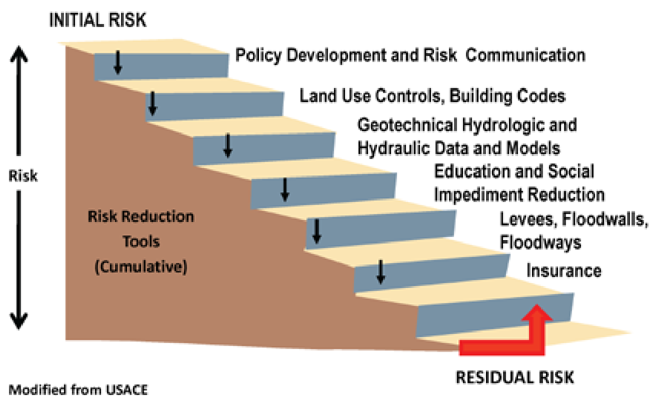


Cedar Rapids Project Facts

- 100-year + 3 ft. BCR= 0.4; 500-year + 3 ft. BCR = 0.5 (USACE)
- Average Annual Damages (AADs) used to calculate the economic benefits are relatively low since large floods such as occurred in 2008 are statistically infrequent. (USACE)
- Precipitation expected to increase 21%; river flows 50% (Eugene S. Takle, Iowa State)
- Calculated benefits are only economic (USACE)

What Do I Do That is Best for My Community?

Living with Floods –Recognizing and Managing Risk



Modified from USACE

Breakout Session Summaries

The workshop included a breakout session, during which participants were divided into four groups to facilitate discussion. Moderators for each group were asked to guide discussion around the four questions listed below. Each group reported on the highlights of their discussion to all workshop participants in a wrap-up session, and these are summarized on the following pages.

1. **What can or should water managers do in the near term to account for both observed trends and potential future nonstationarity?**

   * Where have current methods that assume stationarity failed?

   * Do we have enough of a handle on observed trends (i.e., do we know their causes and how likely they will persist into the future) to explicitly incorporate them into statistical models?

   * How can uncertainty in hydrologic frequency estimates be characterized and used in planning? What are specific management methods to deal with nonstationarity?

   * What are some methods that are currently being used to account for climate change and variability? (Used by operating agencies rather than for research.)

2. **What are future analytical tools that water managers need researchers to develop for dealing with both observed trends and potential future nonstationarity?**

   * Where do we have ambiguities or conflicts in our terminology, understandings, and approaches (within the agency and research communities)?

3. **What are the priority research questions that should be addressed?**

4. **What are near-term actions that should be considered by federal agencies?**

Group A Breakout Session

1. What can or should water managers do in the near term to account for both observed trends and potential future nonstationarity?

Different groups may have different time scales when dealing with operations versus water planning. The following definitions were provided by three different groups:

Water suppliers

- Long term is monthly time scale
- Operational – daily time scale
- Look ahead – 30 years

USACE

- Planning – 50 years
- Operational – Daily

Reclamation

- Operational – monthly time step, 1-2 yrs
- Planning – monthly time step, 20-40 yrs

The final decision was that a planning timescale is multi decadal and an operations timescale is about a year. The difference between these two parties are that operation managers have to deal with current dry periods or wet periods and are not worried about future conditions whereas the goal of planning is to have real time operations be based on future conditions. Many of the products of planning, such as rule curves, that we operate under may have to change in order to adapt to climate change. Another important issue to consider is that operations and planning are done by different groups. A disconnect is guaranteed to happen unless an overlap exists.

Proposals for adapting to climate change is find a window of opportunity to make water control techniques and operations planning techniques more flexible. The Corps traditional uses a rule curve developed for a project area. If we have good examples of a more variable rule curve that can respond to current conditions and climate indicators, it will be easier with whatever budget for some projects to bring in more variable guide curves. A possibility is to shift the rule curve that is based on a frequency distribution in order to adapt for predicted or observed changes. The goal is to have more variable response that can account for water supply and flood potential at the same time.

An interesting example from the Philippines was presented in which people were comfortable with the existing rule curve. As an alternative to adjusting the rule curve, projections, risk assessments, and probabilities of being above or below the rule curve were developed. Then decisions could be made based on these risk assessments and an understanding of possible future outcomes was built.

Water quality was also brought up as an important issue, as releasing water results in loss of the coldest water, and it is difficult to control water temperature. Also, the interaction between groundwater and surface water levels in reservoirs must be considered where groundwater levels are dropping.

On the flood control side, balancing of risk and water supply must be considered. We have different discussions for flood risk and FEMA and other types of projects. Right now, we don't consider climate change or nonstationarity. We should because that has the potential to have an impact. When you are promising to provide 500-yr protection – it would be nice to be confident in that protection. Given the assumption of climate change, it is likely that the risk is going to be changing over time. Flood risk reduction projects were emphasized in which nonstationarity can be incorporated that don't only require better flood estimates, but also include new options and possible options of reducing flood risk.

2. What are future analytical tools that water managers need researchers to develop for dealing with both observed trends and potential future nonstationarity?

An important point was made in this discussion - we are getting caught up on semantics in regards to nonstationarity. Without defining nonstationarity, it was agreed that the issue with standard engineering practice is going to be nonstationarity and we are going to need to plan for that. It was decided that planning for historic records is not going to work. Many questions were posed: Can we extrapolate trends that we see? Can we assume variability will stay within the range of paleo records? And can we trust the trends that we detect? There was a general consensus that we need a new method to deal with these changes. There should be greater effort to evaluate analytical tools using new and old decision methods; however, we cannot ignore that we need management and planning methods as well as analytical tools.

The importance of uncertainty was also discussed. We produce hydrologic forecasts that are uncertain and don't think about how they should be used. It was suggested that we invest in the forecast to see how uncertainty would be beneficial to society. If projections have uncertainty, it will be easier to evaluate the water supply risk. We need tools to help us do this. We are not going to be able to reduce the uncertainty soon, but we need resources to make decisions with now. The development of a system that can use short term forecasts (seasonal) will make us more robust in the future. In the long term, we are not in a stage where we can be comfortable preparing for future climate; however, if we need to build something, we should make sure input from the climate science and a robust decision methodology to explore sensitivities to our existing knowledge are used.

The Red River of the North Basin was used as an example in introducing research needs. The changes in the Red River lack physical explanations. It is believed that climate might be the reason for changes, but there is a lack of money and political will to study that right now. Not understanding the interaction of climate and runoff is an issue that needs to be addressed.

3. What are the priority research questions that should be addressed?

- How do we use non-traditional methods, such as climate models, in engineering? Half of the problem is the hydrology community the other half is the climate community.
- What is the value of a transition to a dynamic planning and operations paradigm over static-design paradigm? What is the benefit? Is it flexibility in our water systems so they can accommodate information we have now on different time scales?
- Are there ways that we can incorporate climate information into short term decision processes such as reservoir operations so as climate changes over time, our decision processes can follow and be responsive to those changes?
- Climate scientists tell us climate is changing, yet NOAA atlas is still static. Could the NOAA atlas tell us what the current change is? What do we see in the record in terms of the influence of climatic changes in rainfall? Do we need to redo all of that to see if there is a signal? Atlas 14 – everything is a stationary process. If there has been a trend over records- we should move our trend up to today. We should update the maps every ten years. Develop frequency analyses with a moving mean and use today's mean.
- We still have to convince the community that point values are just estimates.
- Dam safety – HMR documents. Those are 15-20 yrs old for the entire country. They are the basis for dam safety and evaluation of dams. Updating HMRs including incorporation of long term climate is needed.
- Statistical procedure needed for forecasting probability and risk from records exhibiting long term variability. We assume floods are independent from year to year.
- Propagation of linkages in uncertainty at global scales, continental scales, etc. Understanding where uncertainties come in to quantify what we're going to do. All uncertainties! Good method of incorporating uncertainty into decision making is needed.
- A lot of discussion about climate change deals with reluctance to assign probabilities. The system may change in way that the model can't capture. We have to be robust to things we've never considered- how do you design a system to be robust against things never thought about? Black swan events must be considered– unknown, unknown.
- Black swan events come out of nowhere – look back and think we had no evidence. There are a lot of things in climate that we know something about. We know enough to be able to discuss it. Changes in albedo, land surface,

etc. We don't know what will happen, but we have some information. Example of blackswan: economic meltdown – constraining our funding, taking our resources.

- We must develop methodology to deal with black swans
- Need research on how changes affect water demand, such as temperature increases and demand increases. Look at the maximum days which will stress the system.

4. What are near term actions that should be considered by federal agencies?

- When opportunities for change arise, take those opportunities to assess climate risks and instill flexibility
- Update 17B
- Continue to develop good working relationships with colleges and relationships. Sometimes professors aren't looking for political savvy methods and may be less biased and willing to put work out there and building knowledge base
- Prioritization of what can be done
- Systematically evaluate sources of trends in existing streamflow records for multiple and interacting sources
- Manuals/guidance for climate change related issues
- Get the academy to review FFA question
- Keep advocating for research in various areas that are practical for their needs; tie into NSF and NASAA; peer reviewed literature – department of energy; EPA

Concluding Statements

The breakout session ended with some important final thoughts. A general consensus was that we need an oversight group or multi-disciplinary connection to bring together climate scientists, engineer/hydrologists, and water operators to develop a more efficient research agenda for the nonstationarity issue. A lot of general research topics were provided, and a process for proposing and beginning this research must be established. One approach to identify priority research areas is to look at the decisions that must be made, such as safety decisions, and work backward from decisions to evaluate what information is valuable. Focusing on constraints, such as operating guidelines that are laws, was also suggested to determine how we can respond in a flexible manner. A priority research topic suggested was to identify and validate new options for water managements that address stationarity, such as the ability to assess current storage allocation and suggest reallocation strategies that minimize risk. Another was to determine how uncertainty can be translated to users at various levels. And from the water managers' perspective, a request was made for any guidance that can be used in the field, even if it is not a perfect solution. Water managers may be more apt to believe in climate change if they feel like they have some tools to control the effects.

Group B Breakout Session

1. What can or should water managers do in the near term to account for both observed trends and potential future nonstationarity?

Data-related

- Use of paleoclimatic data
  * Increased perspective on natural variability
  * Use for sensitivity testing of existing systems
  * Entry point to new kinds of information
- Monitoring
  * Need for continued monitoring and timely analysis of monitoring data

Robust Planning

- Ability to deal with change form any source
- Define and communicate performance measures and goals
- Increase ability to adapt systems
- Assessment of when, why, and how systems fail and planning to deal with system failure
- Short- vs. long-term planning horizons
- Benefits of adaptive management: always in change-mode so more responsive to change
- Change from certainty/uncertainty approach important but requires time and effort; purge certainty/stationarity language

2. What are future analytical tools that water managers need researchers to develop for dealing with both observed trends and potential future nonstationarity?

Uncertainty

- Tools for analyzing/assessing uncertainty
- Decision and planning tools better able to incorporate uncertainty
- Better characterization of uncertainty in GCMs relative to natural variability
- Holistic management of uncertainty from infrastructure to management plans to communication of expectations

Change-detection

- What is/isn't changing
- Source of change – processes driving change
- Ability to identify/detect changes in extremes

Vulnerability assessment

- Modeling of only pertinent factors
- Simple bottom-up prioritization methods for people on the ground

- Ability to accommodate existing variability

Information use and availability

- Guidance document for use of GCM output
- Increase availability and utility of existing tools
- Use information we already have
- Communication about data limitations and caveats
- Increased quality of seasonal forecasts

New and improved models

- Better understanding of hydrologic processes based on data mining

3. What are the priority research questions that should be addressed?

Update and improve existing tools

- Bulletin 17B
- Better characterization of historical surface weather
- Better characterization of historical land cover changes
- Existing weather, climate, stream flow, etc. databases
- Continued and expanded monitoring, including maintenance of monitoring infrastructure
- Re-focus from climate to water research

Cross-boundary communication

- Funding for teams of modelers and model users
- Avoid implementing adaptation strategies in one sector that create vulnerabilities in other sectors
- Regional climate/climate impacts centers

Better understanding of integrated information use

- How to use information of questionable fidelity for decision-making
- How to better combine information from people in multiple sectors and sources for decision-making
- Case studies of adaptation processes

4. What are near term actions that should be considered by federal agencies?

Interagency collaboration

- Improve methodological consistency
- Resource and information polling
- Synthesis and development of best-practice guidance and incorporation as appendices in existing documents
- Work similar to BOR-led Colorado River project.
- Value process as much as product

Training and retaining skilled and knowledgeable staff-level employees

Increase ability of managers to lessen risk/increase resilience by using existing tools

Pay more attention to information transfer to developing countries

Invest in maintaining and updating observations, monitoring, analysis, and standards

- Bulletin 17B
- Increased analysis of precipitation frequency analysis and PMP
- Increased monitoring investing
- Evaluate budgeting priorities re: research vs. implementation
- Continue water census

Group C Breakout Session

1. What can or should water managers do in the near term to account for both observed trends and potential future nonstationarity?

Purpose

Not everyone has the same requirements and exposure. Need to specify purpose, i.e., dam safety or water supply or whatever. You would get different answers for different areas. What is the specific purpose for the question the manager is posing? It also relates to time line you're working on. Need to balance the risks, and take into account the individuality of the issues.

Robustness and Flexibility

- The water managers may in fact make decisions that do not require very accurate info from climate. They can make robust decisions with an imprecise answer from the climate community, but there need to be some education so that there is some understanding about what climate science tells us, and the whole system evolves in a healthy way.
- Our ability to tell water managers what the risks are can change with time. They need to be receptive to allowing those things to change.
- An example in medicine – doctors make a decision based on what they know now, because you have to make a decision, but you're constantly researching it and you allow for further information to be incorporated in the decisions in the future.
- We are facing long-term changes that we don't fully understand. You can reduce your chances of disasters by revisiting your plan on a regular basis. That's an obvious thing for water management BUT we have $million hydrodam projects that are locked in for 50 years.

Learning and Updates

- We should be updating our understanding and taking advantage of new tools, seasonal and regional forecasts to better understand processes. Need to use all the tools currently available before looking at new information.
- But there are lot of people who are unwilling to change and adapt new approaches and new information that tell us how the system is evolving.
- Another aspect of learning process –we have guidelines for controlling dams which are supposed to be updated, but funding is on a decline and in the dam safety world things that should be done are stalled by the funding. The failure of water managers has been to effectively communicate their needs to congress. How do we say we need to update our learning when there are other financial pressures – war, health care, etc?

Encouraging Joint Effort between Scientists, Decisionmakers, and Practitioners

- Things that we're doing such as using paleoclimate information is a success story on incorporating climate variability in hydrological studies. In some places, it's on the table to take the next steps and include climate impacts. The picture is not so rosy looking at other sites. Some are trying to incorporate nonstationary methods into specific projects but there is no continuity and coherence even within agencies.
- We need closer collaboration between hydrologist and climatologists on physical processes between areas. Better for water managers to have a team dialog for water supply to collectively understand problem - water supply question, flood question.
- On a temporal scale - planning vs operation and management. We are looking out many years. Design looks way ahead, Planning looks ahead a little, operation only looks out to near term. I think we need to figure out how to put those together. How to formulate management rules for all of these different spatial and temporal scales?
- Language issue – definitions and confusion between projection/predictions/ etc. In stochastic community people have ideas on language (for example, on what nonstationarity means).

Communicating Uncertainty or Levels of Uncertainty

- Important for decisionmakers to understand uncertainty.
- For example,very generally, we have more confidence that temperatures will rise than we do about what precipitation will do. It will be warmer, but it could be either wetter or dryer.
- With rising temperatures, if snow and ice has been important to a system, then things may change in dramatic ways. But even in that there are questions – groundwater recharge – but we do know something about storage (snow) will be reduced.
- Water managers have more control over demand than over precip
- Look at water system and see if its temperature driven – if it is then you should definitely be looking at that. If not, then you should be building for resiliency since we don't quite know about that.

2. What are future analytical tools that water managers need researchers to develop for dealing with both observed trends and potential future nonstationarity?

- Consider nonstationarity not just in water use, but in other areas: land use, etc.
- Water managers need a characterization of climate system. They need the tools in order to make the decisions.
- To see the consequence of climate, land use etc we can just take a scenario approach and run it through some models. Similarly, could factor nonstationarity into those tools. The big problem is that people think that the tools will solve the problem – but the existing methods are not appropriate always; the whole system needs to be explored not only the particular tool. What do we do with the information?
- Given the uncertainty, for lots of reasons the current decision-making process is not always accurate. The decision making and then the operations, planning and guidance processes all need to be addressed
- We need to reevaluate the decision-making process and tools at intervals because at some point the system breaks. The tool becomes unusable because it is unrealistic at some point, and gives wrong decisions.

3. For both near term and longer term research-oriented actions, what are the next steps that should be pursued?

Focus on improvements to GCMs and connection between climate & hydrology models? Do you see that as the way forward, or is it improvements to decision-making that needs to happen?

- There are many issues that are simple that need to be addressed: hand off between climate and hydrology models, scale and bias.
- Plus there's a concern regarding the link between climate and hydrology beyond just reformatting the files as you pass it back and forth. We have knowledge and insights in climate models and we know what they are good at. Can we combine the good stuff that comes out of the GCMS with our experienced knowledge of the atmosphere? How do we use the knowledge between the large and local scale processes and apply it to the climate model projections information to create intelligent scenarios?- Conceptualizations in hydrological models are not up to the task when dealing with GCMs global information, for example evapotranspiration or radiative values.
- Right now climate models are on monthly time step. Most hydrologic models disaggregated into daily and ignore the statistics from the climate model. In recent years there has been daily information, even 6 hourly in models. But concern is that daily statistics are lousy.
- We could do better in describing processes in hydrological models with research. Let's go to a regional model and couple with soil moisture so we're not arguing about which models suck and move on to which processes we can agree on and focus on.
- We should work toward merging climate and hydrologic models instead of feeding the climate data into the hydrologic models.
- We are just now at the stage where we an match up the scales of necessity. The scale of the GCMs and the downscaled data is closer to the requirements of the hydrologic models.

- We need to look at other forcings than what we've focused on – land and water management. We need to do better looking at some very important factors that we might be ignoring – irrigation, deforestation, etc. that might have a large impact.
- There's a difference between doing science just for understanding and for water management and hydrology. How decisions are made is an important factor in what we study.

4. Other Considerations and Points

Reinvigorate Research and Capabilities

- There is a need to reinvigorate research activities. we need to reanalyze our methods for incorporating climate research into operations in the federal agencies
- Human capital. Single most import thing to do is to ensure adequate pipeline of thoughtful well trained professionals– engineers, researchers, working in the research institutions and in the organizations responsible for decisions. You saw data on Red River of North and agencies say we don't have people to look at that. The number of skilled people in agencies is getting smaller.

Uncertainty

- There is a conflict what's available and what we know. What we expect is more.
- We need to assess language regarding uncertainty. Have we tackled the stationarity language – there doesn't seem to be agreement in the water agencies let alone ability to talk to the climate community.
- We don't just need better info to cope with uncertainty. We need to cope with uncertainty in different ways – adaptive approaches, maybe redoing guidelines not just adding a paragraph to the existing.
- It's important to continue the research that would get us to better understanding and estimating of the process and uncertainty, and continue with some tool building. I think that the simulation of floods and other water issues that come from putting various climate scenarios into water models is the best picture we have right now to see what is going to happen. As opposed to putting them up to stochastic methods.

Model Reliability

- Reaction to models from water community - there need to be some education about what models are, to reduce fear of unknown across disciplines
- Seems to be strong degree of skepticism in what climate models do. Skepticism in regard to GCMs; GCMs are just one of the ways to construct projections of possible future; need to cope with uncertainty in a more flexible way.
- There's a tendency for hydrologists to see climate projections as immediate input in hydrologic models, which is risky and dangerous. Weak point is climate projections. This is a wide view. It's flawed. The hydrologic models are not up to the task and the process of connecting to the hydrologic model is ripe with sources of error. Process understanding is weak, need to keep working on research. The research on land processes is not over. Climate people look at detection of change to see if model can explain what happened in the past. We need to do a similar analysis on our land models hydrologic model to see if they're adequately working. Need detection and attribution studies using hydrological models, similar to climate attribution and detection studies. I worry about the things we're not worrying about. It's not sufficient to take changes in temp and precip and plug it into hydrologic model.

Data and Analysis

- Make sure we maintain carefully monitoring key variables that describe hydrologic environment. Those records are precious and important and shouldn't be eroded. We have to increase greatly the effort to analyze those records – asking different questions, tease info out of them and be clever in how we look at them to describe the changing status of the environment. Put knowledge from data into practice updating FFA, rainfall analyses, and methods for doing those.

Group D Breakout Session

1.What can or should managers do in the near term to account for both observed trends and potential future nonstationarity?

Where have current methods that assume stationarity failed, if anywhere?

Define failure

- Failure to predict
- Over-predicting - risk vs. cost. Failure is also if what is expected doesn't happen.
- Failure to diagnose and adapt

Our view may have failed

- Failed to assume independence
- Used wrong estimate of 100-yr flood when nonstationarity exists
- Assuming stationarity in physical/developed system
- Using wrong repeat frequency of natural disasters

Reframe question! What are problems of old methods?

Do we have enough of a hand on observed trends (i.e., do we know their causes and how likely they will persist into the future) to incorporate explicitly incorporate them into models?

Need a mixed portfolio

- A full portfolio needs to include stationarity
- Don't just create a new 'normal'
- Everything that is still standing benefits from stationarity
- The past is deterministic, but we should adopt a nonstationary description for the future

Identify the relationship of the trend to the decision environment.

- We understand some trends more than others, e.g.urbanization; ongoing diagnostic studies are important to understand changes and to adapt
- Can identify flexibilities, but do not have institutions to implement them

How can uncertainty in hydrologic frequency estimates be characterized and used in planning? What are specific management methods to deal with nonstationarity?

- The distribution tails are not being included.
- Are we doing the best we can in responding to risk (e.g., land use changes)?
- How do we make decisions–decisions being made are not commensurate with the available information.
- Identify vulnerabilities–responses have not happened even though we have known about it for the last 40 years.

What are some methods that are being used by operating agencies to account for climate change & variability?

- Haven't heard a lot about hydrological methods
- Need to bring in robustness, but be careful–we don't yet know what we are doing.
- Keep stationarity and test extremes
- More work needs to be done

2. What analytical tools are needed?

Distinguish 'analytical' versus 'technical'

- Analytical is procedural

How many years into the future?

- Depends on questions asked by each person

Need better connection between climatologists and hydrologists…big technical gap

- This is a process gap that can be overcome by collaboration

Critical decision making is more complex than decision support and models

- What is acceptable to people who bear consequences?
- What should scientists and managers talk about?
- Major improvements will occur if we talk with each other
- But this raises conflict in competition for funding

3. What are the priority research questions that should be addressed?

Near Term

- Collaboration to resolve disconnects between what the monitoring data says and what the projections say
- Series of case studies based on outcomes of discussions in workshop
- Hydrological and water management research–needs to be on equal footing with climate research
    * Water community needs to be more critical of climate research
    * Develop hydrological approaches as alternatives to GCMs
    * Bayesian and stochastic methods: good basis but not widely used
    * Distribution of different fitting methods and what is used in 17B
    * Use of mixed portfolios
    * Policy community: Intersectoral water management, e.g., water/energy
    * Describe limits of what we know. Drivers of local climates we do not know. (Can only predict ENSO, but isn't the only driver of regional and local climate). Characterize what we may be able to know.
    * Define scientific meaning of uncertainty and strategic use of uncertainty
- What drives use of new tools, models, and data? What leads innovative research to be adopted?
- Need a mechanism to query research

Long-term research

Do what is recommended in WUCA report.

Climatologists - incorporate physical things we know about

- interannual variablility
- integrating higher moments into models.
- increased definition of climate models & nesting models
- statistical, dynamical modeling plus higher resolution modeling

Methods to do multi-scenario analysis, allowing rules to change over time

Where in robust decision making do foreseeable surprises come into play?

How to organize scientific information in a legitimate way that incorporates multi-scenario analysis

4. What are near term actions that should be considered by federal agencies?

Interagency coordination to create incentive structures to enable adaptive management

Identify what is not working well and look for near term feasible fixes

Research that is funded should be based on science not politics

- Mitigation research overwhelms funding for adaptation

Recommendations and Next Steps

Rolf Olsen, U.S. Army Corps of Engineers, Institute for Water Resources

Two of the objectives of the Workshop on Nonstationarity, Hydrologic Frequency Analysis, and Water Management were to (1) initiate mechanisms for a continuing dialog between water managers and scientists on methods to deal with climate uncertainty, and (2) formulate an 'Action Plan' for next steps to develop practical guidance for water managers to deal with climate uncertainty. Although the workshop did not reach consensus on how to handle nonstationarity in hydrologic frequency analysis, there were some themes that will be considered for "next steps" by the sponsoring Federal agencies.

Federal Responsibility for Water Data and Analysis

It was clear at the workshop that the Federal government does not do a good job of keeping up-to-date either hydrologic analysis or the methods to do that analysis. Probable maximum precipitation estimates for some regions of the country have not been updated since the 1960s. Some regional precipitation-frequency (PF) estimates were done in the 1960s. The Guidelines for Determining Flood Flow Frequency (Bulletin 17) have not been revised since 1981.

The Federal government should provide adequate resources to keep hydrologic data, information, and methods up-to-date including precipitation-frequency estimates, flood frequency estimates, and probable maximum precipitation. The methods to perform these analyses, such as Bulletin 17B, should also be systematically revised periodically. The Federal agencies must make a case to the Administration and Congress that these updates are important and should be adequately funded. The Subcommittee on Water Availability and Quality (SWAQ) and the Council on Environmental Quality (CEQ) Task Force on Climate Change Adaptation are groups that should push for funding to keep hydrological analysis and methods current.

Stationarity and Hydrology

Most participants agreed that multiple drivers are changing hydrology. These drivers include land use changes, urbanization, and groundwater depletion, in addition to changes in climate. These changes can affect flood and drought probability distributions. Although there was agreement that changes occur in hydrology, there was no consensus on what methods could be used to model either past observed changes or potential future hydrological change. However, cases such as the Red River of the North show the need for guidance on how to handle trends and decadal shifts in hydrologic time series.

Hydrological frequency analysis can go beyond fitting a distribution to data and try to understand the physical processes that are occurring in a watershed. What are the factors that are changing and how do they affect floods and droughts? What are the mechanisms including climate processes that cause hydrologic extreme events? How are these mechanisms expected to change in the future? These are questions that could be considered when doing hydrological frequency analysis.

Participants from the Bureau of Reclamation and U.S. Army Corps of Engineers met to discuss what action should be taken based on the workshop. They felt that a sub-group under the Climate Change and Water Working Group (CCAWWG) should be formed to further evaluate methods. CCAWWG was composed originally of the Bureau of Reclamation, the Army Corps of Engineers, USGS, and NOAA and now includes EPA and FEMA. The aim of the sub-group would be to develop "best practices" for addressing nonstationarity in hydrologic frequency analysis and water management. The "best practices" document would not be official guidance, but could still provide methods for practitioners to follow. They recommended that the group would be composed of Federal agencies so it would not fall under the Federal Advisory Committee Act (FACA). Federal agency participation would include all agencies with an interest in hydrologic frequency analysis, such as the CCAWWG agencies and the Natural Resources Conservation Service (NRCS) and the Federal Highways Administration (FHWA).

Climate Information and Water Resources Planning

One issue in the workshop was how water managers should incorporate climate information into water resources planning. On the one hand, global climate models have multiple deficiencies; they don't contain some physical processes and other processes are poorly represented. There are many sources of uncertainties in the models, including forcing uncertainty, initial condition uncertainty, and climate modeling uncertainties (Stainforth, these proceedings). Climate models provide information on a large grid size, while decision makers need information at the local and regional scale. Downscaling climate model output to smaller scales increases the uncertainty of the information and according to one workshop participant, “downscaling may help people do the wrong things more precisely.” On the other hand, climate model output does provide some plausible scenarios of future climate conditions which should be considered in water resources planning and looking only at the historical record is like riding a bicycle facing backwards. General Circulation Model based projections provide some insights, even with their deficiencies.

One approach assumes there is an historical envelope of variability (Brekke, these proceedings) and that future climate can be described by a different and changing envelope. The presentation by David Stainforth showed that the “envelope” given by the current ensemble of climate model simulations “significantly underestimate uncertainty in the potential regional response to increased atmospheric greenhouse gases.” In this view it would be a mistake to try to constrain or reduce the uncertainty in climate models. The challenge as Stainforth notes is to extract and present relevant and robust information while fully describing the uncertainty of the information.

Federal agency climate scientists, hydrologists and water resources managers should coordinate the validation of climate models in order to evaluate their degree of uncertainty and their application in decision making. The Federal agencies are planning another workshop in August 2010 on “Assessing a Portfolio of Approaches for Producing Climate Change Information to Support Adaptation Decisions” which will investigate this issue in more detail.

Uncertainty and Decision Making

Some workshop participants pointed out that there are inherent irreducible uncertainties in climate science, so water managers need to make decisions under uncertainty. Water managers should be concerned with making better decisions, not necessarily better predictions of future climate. At the workshop, speakers presented some methods to make decisions under uncertainty that are not typically used by water management agencies now. Lempert presented robust decision making, which is an iterative framework based on a vulnerability-and-response option rather than a traditional predict-then-act framework. Brown said water managers need to shift from a static design paradigm to dynamic management and gave an example of its application in the Great Lakes. Waage discussed alternative methods that are being considered by water utilities. These methods should be considered by Federal agencies for their planning processes.

There was some debate at the workshop over how much flexibility a Federal water management agency has in its decision making and planning process. Both the current and proposed revision of the Principles and Guidelines (P&G) used for water resources planning require that evaluations of alternative plans should be based on the most likely future condition, which is very uncertain with climate change and other potential changes. In addition, the P&G generally employs a decision methodology that requires an optimization approach that assumes we can assign well-defined probabilities to future conditions. The issue of the best methods for planning given an uncertain and changing climate is currently being discussed among CEQ working groups.

The Corps of Engineers has a team to develop planning methods for making decisions under climate uncertainty and is encouraging other federal agencies to participate. The USGS Biological Resources Discipline and the U.S. Fish and Wildlife Service are encouraging research into the use of adaptive management and structured decision making to deal with the uncertainty of future climate.

International Next Steps

The workshop also had an international focus, and there are also international next steps following the workshop. The United Nations (UN) Secretary General’s Advisory Board on Water and Sanitation (UNSGAB)/ High-Level Expert Panel (HLEP) on Water and Disaster recently published *Water and Disaster*, a report of action plans to reduce the impact of water-related disasters. Dr. Takeuchi discussed this initiative at the workshop. The Commanding General of the U.S. Army Corps of Engineers (USACE), LTG Robert Van Antwerp, is a member of this HLEP and has asked that the USACE lead the Task 29 action: “National and international hydrological institutes must take the initiative to identify underlying analytical and data requirements to meet climate changes that are likely to be highly uncertain and so as to support structural and non-structural measures for disaster risk deduction.” This action is similar to the next steps proposed by the U.S. Federal agencies: to develop best practices for hydrologic frequency analysis for changing conditions, for how best to use climate model information in water resources planning, and for making decisions under climate uncertainty.

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